Skills Alliance for Industrial Symbiosis: A Cross-sectoral Blueprint for a Sustainable Process Industry (SPIRE-SAIS)

Industrial Symbiosis and Energy Efficiency in European Process Industry: State of Art and Future Scenario

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Summary

1 Executive Summary

The objective of this deliverable is to describe the current state of the implementation of the Industrial Symbiosis (IS) and Energy Efficiency (EE) concepts in the European Energy Intensive Industries (EIIs) (Task 2.1) and the possible scenario for a sustainable industry cluster, following the upcoming developments in Circular Economy (CE) (Task 2.2) and allowing their evolution to enhanced cross-sectorial cooperation for sustainable growth and combined strengthening of competitiveness in the global market. In addition, a future scenario describing the process industries operation in five to ten years, incorporating the main categories of technological developments together with the related required skills and competencies is developed (Task 2.3). The achieved results has provided the foundations for industry skills requirements in WP3 and VET system in WP4. In addition, they contribute to the basis for the Blueprint development in WP5.

IS refers to establishing multidimensional synergies, including economical, social, or environmental aspects, across different industries. The economic synergies result from the production of marketplaces for underused resources, resulting in revenues and cost savings. The social impact often refers to jobs generation and to promoting relationships with communities surrounding the industries, while in environmental aspects, the synergy is mainly focused on material and emissions efficiencies promoting resource conservation and reducing associated environmental impacts.

In order to achieve the transition towards a CE in Europe, the cross-sectorial IS is a potential pathway for EIIs. In this context, waste, energy, by-products and water are the main streams for the transactions among the different process industries. For instance, chemicals as a resource sink primarily enable energy and waste synergies, while as a source, this sector enables primarily by-products and energy synergies as the chemical sector has a wide range of applications. Concerning the steel sector mostly has a source role in building waste and energy synergies, while as a sink, this sector enables waste and energy synergies. In addition, the cement sector tends to act as a sink developing waste synergies, while as a source, it enables energy and waste synergies. The technology insights cover a collection of technologies for energy, waste, by-products and water synergies.

IS and EE across sectors include relevant technologies per category and building from cases that are common to the various sectors. In particular, technologies most commonly applied are ad-dressed at a higher level in terms of stream categories: energy, by-products, waste, and water. These technologies apply to all sectors for both internal optimisation and symbiosis with others. Both waste and by-product categories can be reused as raw materials in other sectors and specific technologies and processes for each type of material are required to separate the valuable fractions, by direct application or multi-step processing. On the other hand, new technologies, systems and synergies among companies for EE are mainly focused on optimising energy consumption and production, reducing the use of fossil fuels and the carbon footprint of industries as well as investment, maintenance, and management costs of the energy infrastructure.

This document mainly describes the current state of the implementation of the IS and EE concepts in the European process industries, including the transactions of energy and material flows. Based on the current state, upcoming techniques and developments have been analysed on the basis of the main CE transformation levers and related projects and technological market trends. Iron and Steel, Chemical, Refining, Non-ferrous Metals, Minerals, Water, Ceramics, and Cement sectors are all the A.SPIRE sectors which have been considered within this evaluation. In addition, the Waste treatment sector has been considered as a transversal sector for IS. The results of the European (past and ongoing) funded projects, the scientific literature, the official documents and public documents of each sector have been explored in order to describe and define the current state of IS and EE in each sector. Furthermore, some Case Studies and Best/Good practices examples on IS have been taken into account. The effects of IS and EE on the workforce have been also considered in a devoted chapter, by also including training/education projects in the field.

Compared to the first version of the D2.1 (finalised in September 2020), the second version was updated by including new literature, new projects and documents on upcoming techniques and developments in order to analyse the main CE transformation levers and technological market trends related to IS and EE in the considered sectors. In addition, future trends and existing foresight analysis tools, mainly looking at the internal sectoral developed, were analysed to define a Future Scenario for process industry operations in five/ten years in the main sectors considered. Specific objectives on IS and EE for each involved sector, including effects of IS and EE in terms of new skills requirement and training needs were provided.

Finally, the main updated survey results, providing information on the current state of IS and EE in the European process industry have been provided and summarized, aiming at creating the basis for a complete state-of-the-art of IS and EE implementation in process industries. The Questionnaire is provided at the end of this document in the Annex I.

The third and final version of the deliverable was further updated, including new literature, new projects and documents on upcoming techniques and developments in order to analyse the main CE transformation levers and technological market trends related to IS and EE in the involved sectors. In addition, future trends and existing foresight analysis tools were updated by some sectors involved in order to define a Future Scenario for process industry operations in five/ten years related to IS and EE as well as new skills requirement and training needs.

Concerning the cross sectoral developments of IS to be considered there are not only the use of recycled products and transformed materials as raw materials for manufacturing new products but also (product, network, private and public) transaction services between industries that can offer new common market solutions, business and cooperation models. They aim at reducing production costs, implementing new jobs, and including external customers. In addition, other aspects are data management opportunities allowing product customization, new decision and management tools to improve IS. Another dimension highlighted concerns the sustainable development in a region, guidance to local and regional authorities and promotion of public dialogue processes to ensure regional action plans, and interregional learning and capacity building.

Concerning EE developments across sectors, they are focusing on new technologies, systems and synergies among companies to optimize energy consumption and production to reduce the use of fossil fuels and the carbon footprint of industry as well as investment, maintenance, and management costs of the energy infrastructure. Technology transfer and application is exploiting of best available technologies including digitalisation, integrated control systems, artificial intelligence, consumption measurement and preventive maintenance. Replicable instruments for energy cooperation, business models, joint energy services for industrial parks are elaborated. In addition, amendments to existing regional/national/EU policies and legal frameworks to simplify energy cooperation/services at all governance levels are highlighted.

Concerning the workforce adjustment for IS and EE related to their technological and economic developments, it is mainly featured by a multidisciplinary approach, based on green and digital skills and new skills to manage the complexity of cross-sectorial cooperation in IS and EE implementation. The pro-active skills strategy has to consider not only technical but also soft skills for IS and EE. In particular, for IS skills, they include: communication and information, co-creation and cooperation with other sectors and local stakeholders and authorities, managing diversity to involve different stakeholders, materials and recycling know-how, fostering financially attractive paths with a strong positive impact on the environment. In addition, for creating IS facilitator profiles, they include: new skills for networking, collaboration, system thinking, legislation (environmental economics and policy), special skills for waste and recycling, environmental improvement, entrepreneurship, financial, marketing and management skills, MFA (Material Flow Analysis) & LCA (Life Cycle Assessment), Marketing, and Information Technology skills. For EE skills, they include: green skills for the transition to a low-carbon economy; skills to manage managerial and technological changes, specific sectoral skills, integration of EE into daily operational practice in a continuous process; requiring additional skills, and interdisciplinary knowledge related to energy management, renewable energy sources; energy auditing, building and facility management; energy trading, economics, financing, production planning and maintenance. In this context, the transition from Industry 4.0 to Industry 5.0 was highlighted. The EU Industry 5.0 approach concerns the human-centric orientation as well as the integration of sustainability, resilience into industrial value creation. It is based on the humanisation of the technological environment in human cyber-physics system (HCPS), including the workforce in the CPS by creating HCPS, and developing technology for the people and solutions to societal challenges. In particular, this transition aims at developing systems that use renewable energy and reduce waste through the collaboration between man and artificial intelligence. Consequently, in the context of Industry 5.0, robots will be collaborators rather than competitors in the near future. However, AI can cause significant issues for the workforce if it is not supported by training and skills improvement activities focused on the use of advanced digital tools. New skills requirements will provide advantages not only for workers but also for companies, providing benefits for their competitiveness.

The company survey across the different sectors reflected that the current level of technological implementation is higher for EE rather than for IS, although companies perceive IS and EE as an important chance to emphasize their efforts in the future toward both topics. In addition, some barriers belong to implementation practices and perception of solutions generating new skill demands in any category of workers. The main barriers are the cost of investments, working across different sectors, integration of regional stakeholders, regulatory issues, outdated plants, infrastructure and equipment, cooperation challenges, and skills gaps. The current level of skills is generally lower for IS than for EE. Furthermore, the current training measures implemented by companies are mostly not formal and unstructured, and emerging and future skill gaps will be overcome by internal and external training activities. The skills that mostly need to be updated in the incoming 3-5 years are identified in specific job-related skills, digital and personal skills. Other useful skills identified within the survey are regulatory skills and entrepreneurship.

Based on achieved results, future trends and existing foresight analysis tools were analysed and applied, to define the future scenario for process industry operations in five or ten years. In particular, specific objectives for each sector on IS, EE technologies and processes as well as on new skills requirement and training in the different sectors can be summarized as follows:

- Developments of monitoring systems and new sensing devices for improving characterisation of process inputs/outputs to a better and targeted valorisation of by-products were analysed in the different involved sectors. It was highlighted the importance of making manufacturing and processing stages more and more predictable for reducing the spreading by-products characteristics and for increasing their recovery as well as creating added value for multiple sectors to reduce and valorize waste flows. Online measuring and monitoring, with dedicated sensors within a hardware and software architecture, are crucial to supervising the whole process. On the other hand, real-time data-driven monitoring and process control and online monitoring systems for control of pre-treatment steps and data-driven cloud-based control system are fundamental for different sectors.
- Digital technologies, that will allow smart and fast information exchange and seamless connection of different industrial production cycles for most of the involved sectors are: Artificial Intelligence, Digital twins, Digital Support System, Cloud-based Smart Waste Management systems, Robotic systems and Model and matchmaking algorithms generating ideas for synergies. Furthermore, other important digital technologies will include Digital Intelligent Sensor Management (ISM) technology, integrated in the probes, process control with Twin digital sensors, Optical separation Intelligent system for elimination of heavy metals and possible pollutants in off gas. In addition, digital technologies in manufacturing processes will allow optimizing the energy mix. In addition, an integrated digital knowledge management system with which up-to-date system information can be shared and traceable with supervisors, and can allow studying the consequences of potential measures by means of scenario planning.
- Future demand and market requirements with regard to environmental and demographic challenges are linked to the achievement of the carbon neutrality by 2050. For improving and expanding by-products recycling in the field of applications, flexible technologies, easily handling, distributed and not centralized, cheap and easy to manage, will be a great input for producing materials to be used in other industries. Improving product design, by requiring easier and more efficient disassembly, traceability, and recyclability of by-products will be crucial. In addition, the following fundamental aspects in different involved sectors will be important: development of new exploitation and valorisation schemes based on business models and services tailored; new governance approaches; reducing barriers for recovery, reuse and commercial exploitation of valuable resources in IS; novel models of collaboration between stakeholders.
- Transforming a by-product or a waste in an input material or energy for another industrial process will lead to standardization to extend production controls, quality measurements, logistic cares to the new product. For this reason, new skills and training of people will be required as the future effects of the uptake of IS on the personnel. This means that workers will need to be trained in handling more and different waste streams as well as in engineering and advanced process control. In particular, digital competencies will be required for personnel along the whole value chain, but also vocational training, skills update, re-skilling will be implemented.
- Effects of the uptake of EE on the personnel will result in skills and trainings designed for the optimization. Recovery of energy means new processes with new technologies and, consequently, devoted skills and trainings should be anticipated.

Understanding technology trends and evolution in the field, and the ability to learn and integrate new concepts and apply new methods / technologies will be crucial in all involved sectors.

The future industrial scenario implementation will go one step further assessing not only resources and technologies but also the impacts and policy recommendations to achieve an effective industrial roll-out of decarbonization technologies inside and beyond the EIIs.

Concerning projects considered in this deliverable, different aspects are provided in the forms developed for each project: sectors involved, funding scheme (e.g. RFCS, FP6, FP7, H2020, etc.), title and acronym of the project, main key words, start and end date, short description of the project and if the project involves either IS or EE (or both), what kind of flows of Energy/Material are involved, the main objectives and outcomes, the website of the project and the final report (if available). The summary description of each project has been also included in the dedicated sections of the Deliverable. At the same time, forms have been updated and a dedicated folder has been created in the SharePoint of the SPIRE-SAIS project and it will be also made available through the SKILLS4Planet platform. It will include all forms developed for all projects and subdivided into sub-folders related to each involved sector. The repository will be updated continuously taken over by the established SIHub beyond the project duration.

2 Introduction

Over the last few years, in particular from 2014, the scientific interest in Industrial Symbiosis (IS) has increased by recognizing its potential in terms of its environmental, economic, and social aspects. The intensive use of land resources and energy, the increase of industrialisation and urbanisation, and the modern lifestyles have led to increased greenhouse gas emissions, and, consequently, to negative impacts to the environment and to the population. For this reason, finding solutions for reducing CO_2 emissions and for using resources more efficiently, without hindering the economic development, has become urgent. These aspects can be addressed through the implementation of the IS, defined as the approach in which one company's waste is used as raw material by another company. The concept of IS comes from biology where symbiosis is defined as the "association of individuals of different species in a relationship where there is mutual benefit" (Schwarz & Steininger, 1997). An example can be provided by the symbiotic relation between the clownfish and the sea anemone, in which the clownfish protects the anemone from other fishes and the anemone provides shelter to the clownfish against its predators (Miller & Spoolman, 2011). The process of transposition of this concept to industries is made where IS "engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products" (Chertow, 2000). Afterwards, IS is also defined as "a business opportunity and tool for eco innovation" (Lombardi & Laybourn, 2012). The main objective of IS is represented by the increase of production by saving energy and resources through the cooperation among companies that use by-products or waste from other companies (Standardisation, 2018). In particular, this concept is associated with transactions where one organisation acquires underutilised resources from the organisation generating them, and integrates them as inputs into their own production process, with competitive advantages for all participants, in order to achieve economic, environmental and social benefits (Neves, Godina, Azevedo, & Matias, 2019). In addition, this includes also infrastructure and services sharing. This concept can be promoted by several factors, such as saving resources, obtaining economic benefits, meeting environmental requirements (e.g. greenhouse gas emissions), scarcity of natural resources reduction as well as decreasing the waste amount going to landfills and incinerators.

Potentially the IS application includes not only developed countries but also countries with developing economies. For this reason, it is crucial to overcome the various obstacles for the IS development, such as economic, technological, legal, and social ones. In particular, in order to improve the IS application practices, it has been recently highlighted the importance of knowing both drivers (factors that promote and facilitate the development of IS) and barriers (factors that hinder the development of IS) (Neves, Godina, G. Azevedo, Pimentel, & C.O. Matias, 2019). In Table 2.1 are listed the main drivers for companies to find solutions for using resources more efficiently and reducing waste disposal.

Table 2.1: Examples of main drivers that promote and facilitate the development of IS

Main Drivers
Knowing environmental, economic and social benefits
Diversity of industries
Geographical proximity
Stakeholders involvement
Facilitating entities and legislation
Existing legislation, plans and policies (e.g. regulatory pressure and landfill tax)

In the European context, the European Union (EU) aims at reaching a “recycling society” in the long term, by minimising waste productions and by re-using waste as a resource. On this subject, the European Commission (EC) has established a number of directives, communications and funded programs, such as the “Roadmap to a Resource Efficient Europe” communication, which aims at ensuring the sustainable management of resources, according to the economic growth (Commission, Roadmap to a Resource Efficient Europe COM (2011) 571 Final, 2011); the communication “Closing the loop-An EU action plan for the Circular Economy” aims at underlining the importance of IS and promoting the cooperation with the Member States (Commission, Closing the Loop—An EU Action Plan for the Circular Economy - COM(2015) 614 Final , 2015). In addition, the Directive 2018/851 on waste aims at highlighting the advantages of improving the efficiency of waste management and encouraging Member States to implement the IS (Commission, Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste, 2018). Furthermore, European Commission has recently published several directives and communications about the importance of IS (Commission, Measuring Progress towards Circular Economy in the European Union e Key Indicators for a Monitoring Framework 16.1.2018. SWD(2018) 17 final., 2018a) (Commission, Proposal for a Decision of the European Parliament and of the Council on Establishing the Specific Programme Implementing Horizon Europe e the Framework Programme for Research and Innovation , 2018b). Among all these initiatives we can also mention the “Circular Economy Action Plan”, (Commission, 2020) that is one of the main building blocks of the European Green Deal (European Commission, 2019), Europe's new agenda for sustainable growth. After the previous European strategy “Europe 2020”, also based on the rational resource management (European Commission., 2010) and the Energy

Union initiative (European Commission, 2015), the European Green Deal for the EU and its citizens aims at achieving a new strategy for a more sustainable management of materials and resources and more rational practices in waste management and recycling as well as at reaching a complete reduction in net emissions of greenhouse gases (GHGs) by 2050. The European Green Deal strategy is also part of actions for implementing the 2030 Agenda and sustainable development goals of the United Nations (United Nations, 2015), that aimed at preventing climate change by improving the natural resource management. In this regard, the Green Deal strategy and the CE model aim at preserving resources, by allowing their sustainable reuse and creating further value, through changes in the value chain. This implies system change and innovation of technologies, financial models, environmental assessment, society, and politics. In addition, among the most recent European strategy towards a more sustainable economy, the EU Green Deal results in the Climate Law (European Parliament , 2020b), which enshrines 2050 climate-neutrality into law. Furthermore, concerning preservation of resources, the most important initiative is represented by the implementation of the CE concept, growing its policy relevance in Europe (European Commission, 2020a) and involving industry, society and academia as a whole. In this context, energy-intensive industries (EIIs) play a significant role (HLGEEIs, 2019). In 2018, the total direct GHG emissions from EIIs in the EU represented 15% of EU-28 total GHG emissions (Eurostat. Air Emiss. Acc. NACE, s.d.). However, from 1990 to 2015, EIIs decreased their GHG emissions by 36%, accounting for 28% of the total economy-wide emission reductions by the EU (Wyns, 2018).

Concerning **barriers**, they can be of different nature, such as economic, technical, regulatory/legal, organisational, social, and cultural. Particularly the environmental component was most frequently measured, largely due to international constraints on reducing greenhouse gas emissions, national constraints on emission reductions and the amount of waste sent to landfills and incinerators. Furthermore, the economic component is essential in inducing companies to take the initiative to establish an IS relationship. The economic value of raw materials, particularly if the price that companies pay for waste is not economically advantageous for the company. However, concerning the economic component, not all IS cases can provide economic benefits, for instance, due to lower the price of the raw material than some industrial solid waste. Furthermore, the role of stakeholders in deciding this kind of collaboration is fundamental. Examples of the main barriers are provided in Table 2.2.

Table 2.2: Examples of main barriers that hinder the development of IS

Main Barriers
International constraints on reducing GHG emissions
National constraints on emission reductions
Amount of waste sent to landfills and incinerators
Low taxes on landfill disposal
Lack of policies encouraging IS
Lack of funds to promote IS
Deficient regulatory frameworks
Existing stringent legislation
Companies reluctance to establish synergistic relationships
Lack of trust
Resistance to provide data on processes and generated waste
Uncertainty related to the profitability of the symbiosis network and the associated costs and risks

In order to **overcome the barriers** to practically implement IS solutions, some actions can be strategic. In particular, regulations and policies are important for encouraging or limiting the establishment of IS. The legislation and policies should be clear, consistent, and less bureaucratic. In addition, the economic incentives can promote IS with monetary support for companies. Another relevant aspect is represented by the facilitators, that can provide training on the IS concept to employees and, consequently, can assist the company in creating trust and cooperation relationships. Since a barrier to implement IS consists in data transactions between industries, an industrial sector blueprint as a solution in order to overcome the challenge of information transactions has been recently presented (Cervo, Ferrasse, Descales, & Van Eetvelde, 2020). In addition, it is important to increase investment by governments in research and development into technological innovations by promoting research activities, resulting in advantages in job creation, long-term links between companies and the possibility of the synergy network.

Industries mainly characterized by high energy consumption, (Energy Intensive Industries) such as the chemical, cement, pulp and paper, and steel and iron industries and refineries, represent great potential for measures reducing energy and resource consumption. In addition, waste and water management and recycling also represent prominent measures to make them more efficient and to reduce the negative effects of the processes, through the IS concepts application. In this context, **modelling and simulation** represent a relevant potential to support improvements of material and energy efficiency contributing to environmental and economic sustainability across sectors, by enabling and enforcing cooperation. This is fundamental for a better implementation of the IS and EE across different industrial sectors through a network facilitating the exchange of by-products and unrecovered energy, by improving natural resources protection and revenues generation. On this purpose, to improve recovering and recycling of by-products and wastes, monitoring and controlling production processes is crucial through the exploitation of suitable sensing tools and advanced information processing techniques. They can be achieved by applying Artificial Intelligence (AI), Machine Learning (ML) or hybrid solutions, and by coupling them with physic-based modelling. Physical sensors collect process data and information that can be exploited by modelling and simulation tools in order to achieve information on processes that cannot be directly assessed inline and in real time by sensors. This information includes also the status of some by-products, such as slag temperature and composition. Recently, solutions to complex science and engineering problems have increased their application due to the ability to integrate traditional physics-based modelling approaches with state-of-the-art ML techniques (Willard, Jia, Xu, Steinbach, & Ku, 2021). This emerging field, also referred to as *physics-guided ML*, *physics-informed ML*, or *physics-aware AI,* covers many scientific disciplines. In particular, these inter-disciplinary approaches are receiving increasing attention for environmental and engineering systems, where scientific knowledge is available as mechanistic models, theories, and laws but AI can indeed empower extraction of further knowledge from data and computational efficiency and optimization capabilities. These approaches can be exploited to improve material reuse and recycling. In this context, knowing the chemical composition and properties of input materials to the process, due the variable nature of their properties, is very challenging. In addition, an accurate characterization of by-products enables their optimal valorisation in a CE perspective. On this subject, AI and ML approaches can strongly support material characterization, while advanced process modelling, control and optimization tools can allow adapting single processes as well as the whole production chain (Matino, Colla, & Branca, Addressing the right by-product recovery steps in steelmaking chain: support tools for slag recovery, recycle and reuse, 2020). Modelling, simulation, and optimization approaches can help finding the best route for by-products reuse and achieving information on their possible treatments for their recycling and, consequently, maximizing by-products reuse to improve their recycling rate. Control and optimization problems for improving management of resources can be faced through different approaches, such as Model Predictive Control (MPC), Economic Model Predictive Control (EMPC) or bio-inspired optimization methodologies. These tools can be coupled to the deployment of Cyber-Physical Systems, Internet of Things (IoT), Big-Data Technologies and edge Computing, to improve the processes flexibility and reliability and quality control of products.

In order to enhance managing and optimising resources, environmental impact, quality and productivity, in the short term, innovative multi-critorial optimisation tools targeting different impacts will be applied. On the other hand, the combination of optimization tools with model-based real-time control, in the medium term, can allow fast reactions to changing process conditions and enhanced flexibility regarding variable external factors (e.g. raw material prices, market demand for by products). Finally, in the long term, industrial application and demonstration of through-process real-time optimization can be reached.

Some factors may have contributed to study new IS implementations, such as environmental issues, cases of IS over several years, cases of self-organised symbiosis networks, the existence of facilitators, and more stringent environmental regulations. Environmental, economic and social indicators can allow evaluating the impact of the IS. However, the social ones are translated by some subjectivity and complexity, and it is difficult to obtain data for their quantification (Branca, Vannucci, & Colla, 2009). For this reason, it is necessary to overcome these barriers and to define a specific indicator for IS in order to quantify the total impact of this practice on companies. In particular, comprehensive and quantitative indicators are fundamental for exploring how to optimize symbiosis network in the future and to assess systems (Wu, Lu, & Jin, Quantitative indicators for evolution of a typical iron and steel industrial symbiosis network, 2021). They can provide a scientific support for the development of IS and its extension to other industries. In particular, they help to indicate the organization development of different scenarios and impact of the symbiotic activities and measures. For this purpose, decision makers can chose indicators during setting standards for continuously improving the environmental performance of their organization or enterprise.

Concerning the IS implementation, it is important to understand how different conditions and approaches influence IS evolution. Two directions have been identified (Paquin RL, 2012). In particular, how different dimensions of embeddedness influence different IS arrangement types, and how serendipitous and goal directed processes interact across different IS settings. Understanding these different processes can help to understand the dynamic processes related to IS networks. Furthermore, it is important to understand the role of the governmental policy and to clarify the mechanisms of policy intervention to facilitate the IS implementation. On this subject a dynamic process perspective is crucial as shown by the investigation of the policy translation of Circular Economy (CE) and Eco-industrial Park in China (Jiao W., 2014). However, further studies are ongoing in order to find new solutions based on IS, due to some waste materials characteristics, such as toxicity, as well as to high costs and energy consumption of the related recycling process.

3 Cross-sector research activities

Currently, in the global economy the strengthening of integration processes, the increase of intersectoral cooperation and the internationalization of economic processes are observed. Relevant and promising in this case is the formation of the network model for the creation of added value chains based on the integration of competitive enterprises in innovation-oriented intersectoral clusters.

Going into the vast panorama of national and international research on the subject of IS, intersectoral by its nature, it turns out that it is closely and strongly correlated and dependent on the CE theme. The two concepts often overlap and merge, as the use of IS, such as recovery and redirection of resources for their reuse, means that resources remain in productive use for a longer time in the economy. This in turn creates business opportunities, reduces the demand for earth's resources and provides a springboard towards creating a circular economy.

- **Streams and technologies relations**

IS across sectors uses relevant technologies per category and builds from cases that are common to the various sectors. In particular, technologies most commonly applied are addressed at a higher level in terms of stream categories: energy, by-product, waste, and water. These technologies apply to all sectors for both internal optimisations and symbiosis with others. By-product and waste categories share the same technologies, as the distinction is due only to legal motivations rather than technical ones.

In the context of CE, both waste and by-product categories can be reused as raw materials in other sectors. In this regard, specific technologies and processes for each type of material are required to purify and separate the valuable fractions. Some solutions are direct applied, while others require multi-step processing. For instance, in the steel sector, slag from Blast Furnace (BF) is used as a cement clinker substitute and the alumina rich slag can be used in primary aluminium manufacturing through chemical processing. However, depending on its end-use, the slag may require the application of additional technologies. Another example is represented by streams rich in CO_2, where calcium looping is the technology for the sequestration of carbon emissions in the entire process industry (see EPOS project). Depending on the

source of the CO_2 stream (coal plant, cement kilns, steel furnaces, refineries, etc.), different technologies can be applied for capturing and treating CO_2, such as pre-combustion integrated gasification combined cycle, vacuum pressure swing absorption (PSA), and amine-based solvent capture. Another example is represented by hydrogen content in the coke oven gas; it requires PSA technology to reach the high levels of purity to be used in the chemical industry. Concerning the water management, it consists, for instance, in recovering of water streams onsite, by integrating technologies for purification and optimal utilisation of available wastewater streams. Separation and purification processes are crucial, such as mechanical, physicochemical, and biological techniques for the treatment of wastewater, and a combination of different techniques can be required. For instance, in sludge treatment, methanation, liquid waste incineration, and advanced systems for control, monitoring, and management can be taken into account for using sludge as alternative fuel. In addition, mechanical separation options range from filtration to electrocoagulation, while physicochemical techniques from chemical precipitation to electrolysis. Among biological techniques anaerobic filters and anaerobic membrane bioreactors are the main representative (see EPOS project).
In another study, the techno-economic and environmental implications of shifting chemicals feedstock sources from fossil fuels to carbon-monoxide-rich waste gases from the steel industry have been assessed (CORESYM, 2017). The purpose of this report was to understand the potential opportunities and impacts of CO recycling in current and future value chains between steel and chemical industries. It makes important steps in assessing the sustainability implications of CO recycling for Europe, specifically with regards to reducing carbon emissions and meeting European chemical demands sustainably, providing a clear set of recommendations for policy makers and industry stakeholders.
The approval of the EU circular economy action plan and the "integration of industrial symbiosis and the circular economy" into national and regional development plans indicate how strongly these issues are topical. These indications have strongly promoted the development of numerous projects over the past five years.

- **Projects review**

A first evidence that comes from the analysis and overview of the projects listed below, is that IS and the CE depend on the existence of an efficient institutional interventionist system that considers and does not hinder the priorities of the free market. This conclusion is supported by the observation in the data that countries with the most efficient integration of IS and CE in their development plans have achieved a greater proliferation of IS and CE projects. Countries such as Denmark, Finland, Sweden, which are the most developed in terms of IS and CE, have not limited themselves to developing plans for the integration of IS into their development strategies, but have worked and are working for the establishment of managing authorities tailored to the management needs of such practices. On the other hand, the countries that have not yet fully integrated IS and CE into their technical and regulatory development strategies are the ones that face the most difficulties in applying the innovation results achieved. Hence, it is safe to suggest that IS and CE depend on the institutionalization of a series of interventional measures by public authorities tailored to the specific country and region's needs and the characteristics of the industrial product markets in it. Furthermore, the data revealed that countries that achieve a rapid pace of development of the IS and CE are rewarded by strengthened sustainable and economically efficient growth. Conclusion of this review is that the benefits of developing the industrial symbiosis are as follows:

1. The reuse of waste and by-products can lead to a significant reduction in production costs. Cost reduction can be a determining factor in creating more jobs.

2. Reducing waste increases the sustainability of development in a region.
3. Public employees who are familiar with the concepts of circular economy and industrial symbiosis are updated with the latest innovations in public management. Therefore, the whole function of the public sector could improve.

(HULL, 2018-2021) **CRESTING** will train Early Stage Researchers (ESR) in cutting edge systematic analysis of the process of transformation to a Circular Economy (CE) and Industrial Symbiosis (IS). Establishing a CE (such that the maximum value is extracted from materials and waste generation minimised) is a major policy area within the European Union and elsewhere. Explicitly seen as increasing economic competitiveness and laying a foundation for environmental employment, CE policies are designed to increase resource efficiency and decrease carbon dependency. Previous and ongoing research into the CE and IS, however, has been largely concerned with strategies for implementation. The many different fields of activity comprising the CE, IS (e.g., re-use, recovery, recycling, eco-design amongst others) operate with varying degrees of effectiveness in different places and for different materials. These fields of activity have not been critically analysed as an interrelated social, technical, environmental and, significantly, spatial phenomenon. This programme will advance the critical analysis of the concept and sustainability implications of the CE by the training of 15 ESR analysing CE-related activity and initiatives in a range of geographic and economic settings for IS. CRESTING is divided between 5 work packages (WP) analysing: current discourse and policy contexts (WP1); corporate engagement with the CE (WP2); public sector engagement in the CE (WP3); the potential for local economic development and employment from the CE (WP4); and measuring life cycle impacts and developing sustainability indicators relevant to the CE (WP5). With multidisciplinary and international supervisory teams including non-academic partners within each WP, CRESTING will 1) analyse the sustainability implications of the CE; 2) analyse the spatial dimension of the CE and 3) translate these analyses into specific actions for managing the transformation to the CE and IS.

EPOS (EPOS, Horizon 2020, 2015-2019) project considered 5 global process industries from 5 key relevant sectors . The ambition of the EPOS partners was to obtain cross-sectorial knowledge and investigate cluster opportunities using an innovative Industrial Symbiosis (IS) platform. Such platform has been developed and validated during the project. A longlist of different technological options was created thanks to the cooperation of project partners. Sectors involved: Cement, chemicals, engineering, minerals, steel. Objectives: EPOS's main objective was to enable cross-sectorial Industrial Symbiosis (IS) and provide a wide range of technological and organisational options for making business and operations more efficient, more cost-effective, more competitive and more sustainable across process sectors.

(VULCANOLOGIA, 2015) EPOS project develops a simple and single management tool for exploring industrial symbiosis (IS) across process sectors. A wide range of technology and management solutions is proposed for supporting collaboration between sectors, by making industrial sites more efficient, cost-effective, competitive and sustainable.
From the start of the project, the consortium has challenged its process industry sites to get to know nearby companies from other sectors and understand their plants, operations, site streams and management. Meanwhile, new ways of doing cross-sectorial business are introduced and tested, always starting from a sound industrial pragmatism.
The UGent cluster management surveys map current and potential cross-sectorial IS cases. The prioritisation of IS opportunities from the longlist has initiated early IS deals within the EPOS clusters, inspiring generic business cases with IS potential for process industry clusters across Europe. In parallel, after completing detailed energy studies on the EPOS sites using

the EPFL energy optimisation platform Osmose and merging with the survey findings, the shareable streams are mapped, and virtual sector profiles built. These profiles are an open-innovative way to share industrial information from industries by simulating typical operating modes of a given industry sector. They enable a systems approach and are an essential part of the toolbox.

The case of heat recovery from an EPOS steel site feeding the Dunkirk district heating network (FR) serves as a textbook example of symbiosis. It points to the success factors driving over 30 years of operation on which the database of technical and non-technical indicators for the EPOS toolbox is built.

The new cross-sector IS cases at the Hull (UK) and Lavera (FR) industrial clusters have supported the EPOS toolbox development. The findings were used to challenge the metrics, system settings, functionalities and operating modes of the EPOS platform. Modelled and integrated into the toolbox is also a selection of more than 25 IS-supporting technologies. And not at least, the multiobjective optimisation function of the EPOS toolbox embeds sustainability and economic parameters that allow for the calculation of triple bottom line gains for a given set of IS solutions.

The EPOS User Club grants access to the EPOS toolbox and shares all guidance material on using the toolbox and investing in IS (manuals, background information, generic cases, etc.).

Meaningful outcomes: Technical: Technology and management database for cross-sectorial industrial symbiosis.

(Markatos, 01-OCT-2010 to 30-JUN -2014) **eSYMBIOSIS** - LIFE09 ENV/GR/000300– This Project aims to develop “knowledge-based web services” to promote and advance Industrial Symbiosis in Europe- . eSYMBIOSIS project created a web-based platform to facilitate Industrial Symbiosis , with the aim of promoting more efficient use of resources, by reducing the consumption of raw materials/natural resources and the quantity of waste going to landfill. The eSymbiosis platform was implemented in the region of Viotia in Greece, where it identified many synergies, so facilitating communication between potential partners with matching economic and environmental objectives. One industry’s outputs could therefore become another industries inputs.

Experience from other IS communities was used to create the necessary baseline and to facilitate the IS implementation in Greece. For example, a project report analysed industrial symbiosis practices in the UK, including database solutions, waste stream classification, and the technologies used to exploit IS synergies. Through a sophisticated ontology, the eSymbiosis platform identifies possible synergies using data on the existing material inflows and outflows of the registered industries in Viotia, and matches those with compatible waste-disposal and resource requirements. The creation of an automated platform, to identify possible synergies between industries in a specific region, was the main project innovation.

The automated process to find the best matches takes into account a range of criteria, including distance between resources and users, and the explicit properties of materials describing by each user. Once registered, a company can access a menu featuring the types of waste offered, or requested, and the location of the user. The platform was launched with 75 participating industries.

Representatives from the registered industries, authorities and other stakeholders in the region of Viotia were trained in the use of the eSymbiosis platform, at two training events and through a users’ handbook. This built capacity in the region to facilitate the update of the IS approach. The project disseminated its findings through demonstration workshops, an international conference, publications, leaflets, a layman’s report and its website. The eSymbiosis platform has

good potential for use in other Greek and European regions with similar characteristics. Capacity building and dissemination activities served to trigger greater industry interest in creating an Industrial Symbiosis network. The project's knowledge-based approach has the potential for reporting measurable social environmental and economic benefits. IS is expected to have a great impact on the regional environment and a positive effect on other activities in the local economy. In the Viotia region, fertile land is used to produce a multitude of agricultural products, such as cotton, tobacco, olives, cereals, legumes, vegetables, fruits and nuts, though pollution due to industrial waste is causing significant damage to agriculture. Reducing the amount of industrial waste could therefore benefit agriculture. In the survey performed at the start of the project, it was found that 139 industrial units generate high volumes of wastewater. The total amount of such wastes generated reaches 9 044 m3/day. Most of this is generated during industrial processes, particularly by the leather processing and textiles, food and beverage industries, and basic metal production sectors. If widely replicated, the eSYMBIOSIS project's IS solutions could contribute to a range of EU policies relating to waste reduction and circular economy, including the Waste Framework Directive (2008/98/EC).
A range of indirect socio-economic benefits could arise from the implementation of the eSymbiosis platform in a region, such as the creation and safeguarding of jobs, the creation of new businesses, and business cost savings.
TRIS- Transition Regions towards Industrial Symbiosis- Programme 2014 - 2020 Interreg Europe- Industrial Symbiosis (Ratta, 2016-2021) is a building block of the Circular Economy, a means to sustainable growth increasing resource efficiency and SMEs competitiveness and resiliency. Despite the acknowledged advantages, IS is not yet fully widespread. The challenge TRIS is facing is to enable a systemic uptake of IS in 5 European regions, supporting policy makers to increase the competitiveness of their SMEs by introducing IS practices. To do so, the TRIS consortium will:

- Identify facilitating elements and obstacles and embed them in (or remove them from) the appropriate policy instruments.
- Reach out and engage with the actors that can drive and/or be impacted by the change and involve them in structured local networks.
- Starting from the knowledge already achieved within the Climate-KIC initiative, TRIS will benefit greatly from interregional cooperation, given the diversity in terms of geography, productive system and maturity of IS practices: the City of Birmingham, project leader, is the most advanced, Hungary and Emilia-Romagna regions have already tested pilot projects, while Småland och Öarna and Valencia regions have approached the topic more recently. Industrial Symbiosis Ltd will play both an advisory and dissemination role, acting as a bridge between the consortium and the European perspective.

TRIS is determined to cause the following CHANGES and accomplish the following RESULTS:

- Raising awareness on the concepts of IS and its economic and environmental benefits
- Causing a mind-shift and building a cooperation culture in the stakeholder groups (including SMEs and policy actors)
- Standardize IS practices into regional policy instrument
- Launching tangible initiatives in the regions: reaching out to more SMEs, supporting their business with new IS cases/projects, preventing industrial waste production, testing new governance models.
- Bringing IS to a higher position in the European political agenda

SHAREBOX (SHAREBOX, H2020 (SPIRE-06-2015) Grant Agreement No: 680843, 2015-2019). In this project a secure platform for the flexible management of shared process resources has been developed in order to optimize existing Industrial Symbiosis or synergies among multiple companies on a single industrial production site. Sectors involved: Cement, ceramics, chemicals, engineering, minerals, non-ferrous metals, steel. Objectives: The objective is to provide reliable information to plant providers in order to share resources (plant, energy, water, residues and recycled materials) with other companies in an optimum symbiotic ecosystem. The development of a secure platform for the flexible management of shared process resources with intelligent decision support tools is the main aim of this project. Meaningful outcomes: The synergies facilitated within the Sharebox project cause significant environmental as well economic benefits.

MAESTRI (MAESTRI, Horizon 2020, SPIRE Grant agreement No 680570, 2015-2019) project developed an innovative and integrated platform combining holistic efficiency assessment tools, a novel management system and an innovative approach for industrial symbioses implementation. Sectors involved: Manufacturing and process industries. Objectives: This project aimed to advance the sustainability of European manufacturing and process industries. Meaningful outcomes: A “Total Efficiency Framework” has been developed in the form of a flexible and scalable platform. Such framework has been validated within four real industrial setting across a variety of activity sectors. Based on a holistic approach which combines different assessment methods and tools, the purpose of this framework is to support the strategies within process industries and to help the definition of the priorities in order to improve the companies’ environmental and economic efficiency.

COPRO (COPRO, H2020, Grant Agreement No 723575, 2016-2020): Online data analytics and novel forms of information presentation that lead to a symbiosis of operators and computer-based control algorithms have been developed. The solutions have been integrated into the IT infrastructure of the plants via a neutral integration platform that connects to different IT systems. Methods for the efficient development of plant models as the basis for advanced control, scheduling, and coordination have been considered in this project. Sectors involved: Chemical, non-ferrous metals, steel and water. Objectives: The development and the demonstration of the methods and tools for process monitoring and optimal dynamic planning, scheduling and control of plants, industrial sites and clusters under dynamic market conditions were the main aims of this project. Another goal is to provide decision support to operators and managers and to progress to automated closed-loop solutions in order to obtain an optimally energy and resource efficient production. Meaningful outcomes: Environmental: significant savings of energy and resources are possible by using advanced technologies for monitoring, decision support, optimisation, as well as planning and scheduling. Technical: The developed technologies are of a generic nature and can be applied to all sectors of the process industries and also to production sites in other sectors.

SYMBIOPTIMA (SYMBIOPTIMA, H2020; 01 September 2015 - 28 February 2019) project has introduced the principles of industrial symbiosis in order to increase the manufacturing sustainability of the process industries. An integrated Energy and Resource Management System which offers tools for production scheduling and demand response management and for Life Cycle Sustainability Assessments (LCSAs) has been developed. Sectors involved: Multi-sectorial. Objectives: The main aim was to promote the mutual interactions among different industries for beneficial reuse of flows that could result in a more resource-efficient production. Meaningful outcomes: This project developed hardware for modular “plug and play” monitoring of production plants and an integrated toolset for all thermal energy sources, flows and sinks. Moreover, in order to maximise the reuse of waste, a unique de-polymerisation process for plastics (PET)' has been developed. A scalable network of low footprint sensors for process monitoring and control, as well as tools for energy-aware scheduling of operations in cross-sectoral operations (i.e. optimising multi-plant operation schedule based on availability and cost of energy) are also included.

SCALER (SCALER, H2020 SPIRE Grant Agreement n. 768748, 2017-2020). This project aimed to develop a set of best practices, tools and guidelines in order to support businesses and industrial sites work ensuring sustainable resource use. New spaces for interaction, collaboration and cooperation will be created since the engagement of a broader set of stakeholders are crucial elements of the multiplier effect in industrial symbiosis implementation. 1 000 theoretical combinations were identified and the 100 more-promising cases selected have already been analysed in more depth. Sectors involved: Process Industry. Objectives: The main objective is to provide mechanisms to increase the level of Industrial Symbiosis implementation across the European process industry as well as the development of action plans to industrial stakeholders and communities. In particular, the objective is to deliver tools and guidelines for industry actors in resource efficiency, reuse and sharing. Meaningful outcomes: Economic, environmental and social benefits. A comprehensive solution for understanding, assessing and intensifying the potential of industrial symbiosis in Europe will be provided by this project. A conceptual framework for sustainability implementation through industrial symbiosis, by identifying internal and external enablers supporting synergies to apply resource efficiency, resulting in productivity and competitiveness increase.

TASIO (TASIO, H2020 G.A 637189; 2014-2019) project was a provider of services on the field of industrial symbiosis in the framework of a common language, methodologies and databases. The STORM toolbox contained state-of-the art tools, software, databases, methodologies and expertise, which the partners bring into the project. A tool owned by partners has been shared, integrated and linked one to the others, when possible. Sectors involved: cement, glass, steelmaking and petrochemical. Objectives: The development of Waste Heat Recovery Systems based on the Organic Rankine Cycle technology was the main aim of this project. Other objectives are a reduction of the total cost per electric output and an environmental increase of the sustainability of the energetic intensive industries. Meaningful outcomes: Technical: The development of the innovative direct heat exchangers, the design and modelling of a new integrated monitoring and control system for the addressed sectors has been carried out. Technical: The development of the innovative direct heat exchangers and the design and modelling of a new integrated monitoring and control system for the addressed sectors have been carried out. An industrial-scale ORC demonstrator and based on the innovative direct heat exchanger technology was operating in 2018 in the facilities of Cementi Rossi in Piacenza (Italy). A pilot scale demonstrator has already been built and tested for the production of compressed air with the energy recovered from waste heat.

STORM (STORM, EIT-Raw Mate-rials KIC) project was a provider of services on the field of industrial symbiosis in the framework of a common language, methodologies and databases. The STORM toolbox contained state-of-the art tools, software, databases, methodologies and expertise, which the partners bring into the project. A tool owned by partners has been shared, integrated and linked one to the others, when possible. Objectives: This project provided a unique opportunity for SMEs to access a coordinated group of excellent expertise in the eco-innovation field. Meaningful outcomes:

- a network dedicated to provide services to external customers for the implementation of innovative, sustainable new business and cooperation model solutions for recycling and/or exploitation of raw materials;
- tools to support companies that are interested in implementing practical measures, aligned with the concepts of industrial symbiosis and the circular economy;
- it offered guidance to local and regional authorities;
- it covered in particular valuable materials, such as raw materials, metals scrap, WEEE and end-of-life tyres in order to recirculate in the economy its materials and components.

FUTURING (FUTURING, H2020, Grant Agreement N. 723633, 2016-2018) project explored future scenarios, concerning European Industry, by considering the use of foresight and other Policy Intelligence tools in order to identify critical factors and to overcome barriers as well as to foster opportunities for the EU re-industrialization process. An overall methodology focused on the potential of re-industrialization in Europe has been developed. An assessment of the parameters of the decision making for investment as well an analysis of areas of business case potential in circular economy has been carried out. The policy recommendations were the final step of this project. Sectors involved: multisectoral. Objectives: This project aimed at contributing to define the strategy for the re-industrialization of Europe, by concentrating on the role of Research and Innovation and incoming paradigms such as Circular Economy. Meaningful outcomes: The outcomes of the project are disseminated among relevant stakeholders in several European countries. Economic benefits: possible increase of the European GDP as much as 11% by 2030 and 17% by 2050; annual net material cost saving; Environmental: reduction of CO2 and primary material consumption; Social: creation of new jobs.

SPRING (SPRING, H2020-IND-CE-2016-2017/H2020-SPIRE-2017; Grant Agreement No.767412, 2017-2019). The increase of the industrial uptake of project findings was the main focus of this project. Guidance and recommendations for measuring progress, impact and success of SPIRE projects, a model for mapping project outputs to industry needs, a package of training and network groups to upskill SPIRE project participants, identification of policy gaps and future SPIRE needs, including aspects of skills and training. Sectors involved: Cement, chemicals, ceramics, engineering, minerals, steel, non-ferrous metals, water. Objectives: SPRING's objective was to increase progression towards the SPIRE goals and enhance project return on investment by addressing the needs and barriers of those who make the decisions to adopt process innovations in industry. Meaningful outcomes: An educational module to describe a good-practice methodology has been developed.

SMARTREC (SMARTREC, H2020, 2016-2019). In this project a standard, modular solution to recover and manage waste heat from corrosive, contaminated and intermittent exhaust streams has been developed. Sectors involved: Aluminium, ceramic, cement and glass. Objectives: The development of a standard, modular solution for the integration of heat recovery with thermal storage that valorises medium to high grade waste heat, adaptable to different temperatures and industries has been carried out. Meaningful outcomes: Technical: a pilot system has been deployed in a secondary aluminium recycler and/or ceramic processor valorising high grade heat for continuous energy intensive salt-cake recycling. Potential heat recovery will result in CO_2 savings, reduction in fuel consumption, improve process efficiency and give significant benefits.

SYMBI (SYMBY, INTERREG EUROPE) project brings together 9 partners from 7 countries to diffuse industrial symbiosis and align regional policies with the circular economy package of the European Commission (EC). To support the transition towards a resource efficient economy, the project includes a wide range of activities, focusing on promoting the interregional learning process and the exchange of experience among regional authorities. Project activities include:

- Evaluation and analysis of existing regional and national policies on industrial symbiosis and circular economy.
- Mapping the investment potential of participating regions in industrial symbiosis.
- Identification of good practices and benchmarking of eco-systems of by-product and energy exchanges.
- Prescribing green public procurement as an enabler of industrial symbiosis.
- Promoting public dialogue and consultation process to build consensus and ensure the successful implementation of regional action plans, through the support and participation of key regional stakeholders.
- Fostering interregional learning and capacity building through workshops, study visits, and policy learning events.
- Joint development of action plans to promote the improvement of the policy instruments addressed by the project.
- Increasing awareness, promoting and disseminating the project results and knowledge beyond the partnership.
- Increasing awareness, promoting and disseminating the project results and knowledge beyond the partnership.

Sectors involved: Cement, ceramics, chemicals, engineering, minerals, non-ferrous metals, steel. Objectives: The SYMBI project aims to improve the provisions and support the implementation of policy instruments and measures for the diffusion of industrial symbiosis, to add value, reduce production costs, and relieve environmental pressures through increased resource efficiency and greenhouse gas emissions. The overall improvement is anticipated to positively contribute in regional sustainable development and job creation. Meaningful outcomes: Best (national) IS projects are listed here: https://www.interregeurope.eu/fileadmin/user_upload/tx_tevprojects/library/file_1502280065.pdf

BASF - IS project initiated by world's leading chemical company. Project included such activities as knowledge exchange between employees in different companies. Addressed issues, results + lessons learned presented below. Germany (BASF) p. 42-46

IS implemented in WELTEC BIOPOWER park. Initiated by companies. Bellow presented addressed needs and benefits (WELTEC BIOPOWER – Industrial symbiosis) (p. 97-103)

IS implemented in Chemical industrial Park Knapsack. Initiated by companies. Bellow presented addressed needs and benefits. Germany (Chemical Industrial Park Knapsack – Industrial symbiosis) (p. 104-108).

FISSAC (FISSAC, H2020 WASTE 2014; 1/09/2015 – 29/02/2020) project involves stakeholders at all levels of the construction and demolition value chain to develop a methodology and software platform, to facilitate information exchange, that can support industrial symbiosis networks and replicate pilot schemes at local and regional levels. It aims to demonstrate the effectiveness of processes, services and products at different levels: manufacturing process (closed loop recycling processes), product validation (eco-design of eco-innovative construction products) and industrial symbiosis model (software platform for replicability assessment of the model). Sectors involved: Steel, aluminium, natural stone, chemical and demolition and construction sectors. Objectives: The overall objective of the project is to create a new paradigm for industrial symbiosis towards a zero waste approach in the resource intensive industries of the construction extended value chain, tacking harmonized technological and non-technological requirements, leading to materials closed-loops processes and moving to a circular economy. The ambitions of the project is to demonstrate the model, which is based on three sustainable pillars ,environmental (lifecycle approach), economic and social (considering stakeholders engagement and impact on society), to be replicable in other regions and other value chains scenarios. The FISSAC project creates an innovation action for the improvement of products, processes and services, including demonstration activities for technologies and the FISSAC model, large-scale product manufacturing demonstration and market replicability of the FISSAC model, and technical developments. A methodology and a software platform will be developed in order to implement the innovative industrial symbiosis model in a feasible scenario of industrial symbiosis synergies between industries (steel, aluminium, natural stone, chemical, construction, and demolition sectors) and stakeholders in the extended construction value chain. The platform will then be used to quantify the expected benefits of symbiotic material flows.

Meaningful outcomes:

Manufacturing processes: Demonstration of closed-loop recycling processes to transform waste into valuable and acceptable secondary raw materials; Demonstration of the manufacturing processes of the novel products at industrial scale.

Product validation: Demonstration of the eco-design of eco-innovative construction products (new eco-cement and green concrete, innovative ceramic tiles and rubber-wood plastic composites) in pre-industrial processes, under a life-cycle approach;

Real-scale demonstration of the application and technical performance of eco-innovative construction products in a variety of case studies

Industrial Symbiosis model: Demonstration of the software platform; Replicability assessment of the model through living lab concept (as a user-centred, open-innovation ecosystem, often operating in a territorial context).

FISSAC will demonstrate eco-innovative solutions in the re-use of industrial waste materials through industrial symbiosis synergies among industrial leaders, achieving closed-materials loops driving innovation across product design, development of product-to-service approaches and new materials recovery methods.

INSIGHT (INSIGHT, Secure management Platform for Shared Process Resources, Erasmus+, 2019-2022) offers to develop a new professional profile, the industrial symbiosis facilitator, and the training curriculum necessary for it. INSIGHT is targeting current and future workers of regional development agencies, technology centres, clusters, local and regional administrations, technology parks, as well as any other entity related to the economic development of specific areas of the territory. Sectors involved: Cement, ceramics, chemicals, engineering, minerals, non-ferrous metals, steel. Objectives: Although the potential of industrial symbiosis in achieving green growth and implementing circular economy has been demonstrated, one of the major weaknesses of Europe lies in its inability to transfer the knowledge base into specific goods and services. Stakeholders report a gap between the skills that are supplied by education institutions and the skills that are actually required by industry. EU businesses and related actors need to become more competitive through the talent and innovation. An investment in knowledge, skills and competences will benefit individuals, institutions, organisations and society as a whole by contributing to growth and ensuring equity, prosperity and social inclusion in Europe and beyond. INSIGHT aims to fill this gap. Meaningful outcomes: Industrial Symbiosis Facilitator - Key study based on current knowledge, skills and qualifications regarding industrial symbiosis.

UBIS (UBIS, EUROPEAN REGIONAL DEVELOPMENT FUND, 2017-2019).The aim of the project is to learn from existing industrial symbiosis plants, from project members that already have experience from industrial symbiosis and the planned pilot investment. Furthermore, the project will spread the knowledge and will inspire others to work with industrial symbiosis. The main activities carry on during the project are:

- Tool for industrial symbiosis: based on existing plants and academic research and previous experiences, a tool will be produced for identification and evaluation of industrial symbiosis prospects
- Study tours:
- Initiative symbiosis projects: pilot sites are in Bjuv in Sweden, Malmö in Sweden, Silute in Lithuania, Kalundborg Municipality in Denmark and Kalundborg Utility in Denmark.

Regional networks: Regional networks will be established to facilitate study visits and exchange of experience.

Sectors involved: Overall Industrial sectors. Objectives: The purpose of the Interreg South Baltic project Urban Baltic Industrial Symbiosis (UBIS) is to support and inspire new symbiosis projects. The project will provide tools, implement pilot projects and carry out activities to spread the project results. Since the business aspect is included in the tools, the project partners expect sustainable symbiosis cases, and long-term effects on reduced pollution discharges. In the UBIS project, there are ten partners in five countries that have implemented five pilots – four technical pilots and one soft pilot related to public planning tool. Meaningful outcomes: The four technical pilots are located in Gdansk, Poland, led by project partner Gdansk University of Technology; in Bjuv, Sweden, led by project partner Bjuv Municipality; in Kalundborg, Denmark, led by project partner Kalundborg Utility and in Silute, Lithuania, led by project partner Silute District Municipality. Thus, the pilots represent four very differing countries in the South Baltic region. Furthermore, the implemented pilots have revolved around very differing subjects, although all within the area of sustainability, resource efficiency and industrial symbiosis.

The experience and learning from the existing plants and in the pilots will be documented in a set of tools for industrial symbiosis, which can be used by others also after the project. These tools are available at the project website www.ubis.nu.

POLYNSPIRE (POLYNSPIRE, H2020; Grant Agreement no. 820665, 2018-2022).The recycling and redesigning the plastics value chain are essential in order to reuse plastic waste material and avoid landfill. This project is focusing on plastic containing materials as follows: post-consumer (after products' end of life) and post-industrial (produced during transformation processes from raw materials to final product). To this end, three innovation pillars are addressed at TRL7: A) Chemical recycling assisted by microwaves and smart magnetic catalysts as a path to recover plastic monomers and valuable fillers (carbon or glass fibres), B) Advanced additivation and high energy irradiation to enhance recycled plastics quality and C) Valorisation of plastic waste as carbon source in steel industry. Objectives: Enhance plastic recycling, more efficient energy usage, decrease of the use of primary fossil resources are some of the main objectives of this project. The decrease of CO_2 equivalent and the creation of a roadmap are also some objectives. Establishing a cross-linked relation between plastic, chemical and steel manufacturing industries. Meaningful outcomes: Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) to recycling/valorisation process of the different materials have been carried out in order to demonstrate the economic and environmental benefits.

FP7-POLFREE (FP7-POLFREE, FP7-Environment; Grant Agreement No 308371, 2012-2016) explored drivers and barriers to resource efficiency as well as it created a vision for a resource efficient economy in Europe. Different policy mixes have been proposed for achieving the resource efficient vision. Modelling results have been used to construct different scenarios for decoupling and sustainable use of resources. Objectives: From its new vision for a resource-efficient Europe, the project proposed new policy mixes, business models and mechanisms of global governance through which resource-efficient economies may be promoted. Meaningful outcomes: The main result is that by using fewer resources and serious action against climate change, more jobs, positive economic development and a high quality of life can be obtained.

CICERONE (CICERONE, H2020, 2018-2020): INCREASING COLLABORATION AND ALIGNMENT BETWEEN OWNERS OF CIRCULAR ECONOMY PROGRAMMES. The current fragmentation of circular economy priorities and initiatives is hindering the impact we could achieve. By tackling the challenge in a collaborative and systemic way, we will increase the sustainability of the transition, all the while valorising existing knowledge and resources. CICERONE brings together programme owners, research organisations and other stakeholders to create a platform for efficient Circular Economy programming. Sectors involved: Biomass / Biotechnologies, Chemicals, Construction / Demolitian, Food, Plastic, Raw Materials, Waste, Water. Objectives: bringing national, regional and local governments together to jointly tackle the circular economy transition needed to reach net-zero carbon emissions and meet the targets set in the Paris Agreement and EU Green Deal. Meaningful outcomes: CICERONE is developing a circular economy strategic research and innovation agenda (SRIA), a strategic guidance document on circular economy in the context of the European Union. A focus on systemic change and adopting a cross-cutting interdisciplinary approach is at the heart of the SRIA, addressing eight themes (biomass, chemicals, construction and demolition, food, plastic, raw materials, waste and water) that build on four societal areas that face sustainability challenges (urban areas, industrial systems, value chains and territory and sea) to tackle EU region-wide issues and facilitate the transition to a circular economy; set of joint programmes that tackle the circular economy transition in a challenge-based, systemic way; platform specifically for programme owners (i.e. public institutions that fund and design circular economy relate programmes) to co-design programmes with a variety of countries, regions and cities across Europe.

BAMBOO (BAMBOO, H2020-SPIRE-3-2018 Grant Agreement No. 820771, 2018-2022) aims at developing new technologies addressing energy and resource efficiency challenges in 4 intensive industries (steel, petrochemical, minerals and pulp and paper). BAMBOO will scale up promising technologies to be adapted, tested and validated under real production conditions focus on three main innovation pillars: waste heat recovery, electrical flexibility and waste streams valorisation. These technologies include industrial heat pumps, Organic Rankine Cycles, combustion monitoring and control devices, improved burners and hybrid processes using energy from different carriers (waste heat, steam and electricity) for upgrading solid biofuels. These activities will be supported by quantitative Life Cycle Assessments. Sectors involved: Steel, petrochemicals, pulp and paper, minerals (magnesite). Objectives: The overall objective of BAMBOO is to demonstrate innovative technologies for waste heat recovery, electrical flexibility and waste streams valorisation in four REII (namely, steel, petrochemical, paper and mineral) integrated in a horizontal decision support system for flexibility management.

Meaningful outcomes: The expected outcomes are: Decision support tool for flexibility management: Tool able to provide accurate scenarios for maximising the benefits of the process syngas and waste streams use and valorisation. It will take advantage of the flexibility potential of the plant and will enable industries to interact with the energy market. New technologies for enhancing processes flexibility:

- High-Temperature Heat Pump
- Novel Heat Exchanger for Organic Rankine Cycle
- Flame monitoring system
- Drying process for biofuel production from paper sludge
- Multi-fuel Low-NOx burner.

S-PARCS (S-PARCS, H2020-EE-18-2017 Grant Agreement No. 785134, 2018-2021) presents a sound concept for reducing energy costs and energy consumption in industrial parks, while, at the same time, increasing renewable on-site energy production. The pre-assessment of the seven "Lighthouse Parks" from Spain, Portugal, Italy, and Austria, which participate in the study, has shown a high potential for joint energy actions, many of which are transferrable to the community of S-PARCS Followers in the UK, Sweden, Turkey, Russia, Italy, Portugal, Austria and Norway. Sectors involved: Chemical, Metal processing, Others (wood products and car manufacturing). Objectives: S-PARCS aims at moving from a single-company energy efficient intervention approach to cooperative energy efficient solutions within the framework of industrial parks, thus enabling higher energy savings and the subsequent increase of competitiveness of the companies located in the parks. Meaningful outcomes:

- Replicable instruments for energy cooperation in real-world environments
- Business models for joint contacting of energy services for industrial parks
- Drafts amendments to existing regional/national/EU policies and legal frameworks to simplify energy cooperation/services at all governance levels
- Build capacities and increase the skills and competencies of players from the EU industrial environment for more wide spread deployment of energy cooperation/services.

HARMONI (HARMONI, H2020-IND-CE-2016-2017/H2020-SPIRE-2017, 2017-2019) aims at bringing together all the relevant stakeholders of the process industry to jointly identify, analyse and propose solutions to the regulatory bottlenecks and standardisation needs that hamper their innovation processes and market uptake of their results, necessary to move towards a more sustainable and competitive European process industry. In order to achieve HARMONI's overarching goal, the consortium has developed a methodology for ensuring an effective collaboration of the eight sectors involved in SPIRE Public-Private Partnership to elaborate solutions to the common challenges they face due to non-technological barriers. This methodology supporting collaboration of SPIRE sectors will give basis for assessment of transferability to other sectors as well in training and skills needs and ways to tackle these shortages within the Blueprint that will be developed by SPIRE-SAIS project. Sectors involved: all the 8 sectors involved in SPIRE. Objectives: To set up an effective collaboration of all the relevant stakeholders of the process industry in the field of regulation, standardisation and other non-technological barriers. To bring together experts with a wide range of profiles involved in the day by day life of the production sites. To boost the deployment of technical solutions towards a more sustainable and competitive European process industry through more adapted regulation measures and good practices. Meaningful outcomes:

- List of regulatory & standardisation bottlenecks

- Characterisation of participation of process industry in EU legislative and regulatory process & standardisation cycle
- Recommendations for removing existing regulatory bottlenecks to innovation
- Recommendations for addressing standardisation needs for innovation
- Suggestions for an optimal participation of the PI in EU standardisation process
- Examples of solutions transferred across sectors
- List of areas with high transferability potential across SPIRE sectors
- Transferability toolkit & list of barriers to transferability of innovative solutions
- SPIRE Knowledge Platform & STAIR Platform for Process Industry.

BASIS (BASIS, European regional Development Fund, 2015-ongoing). The focus of the project will be working with SMEs and identifying opportunities to delivery industrial symbiosis benefits within the network, forming the mechanism for delivering the required project outputs of business assists (12 hours). Sectors involved: all sectors. Objectives: The aim of this project is the creation of a diverse network of businesses across the Local Enterprise Partnership (LEP), with the aim of supporting their transition to become more resource efficient and cost-effective business. Meaningful outcomes: New business opportunities will deliver substantial cost savings, generate sales from new markets and contribute towards creating an environmentally sustainable local economy.

Technology Strategy Board Environmental Data: Novel materials for the Built Environment UK (Environment T. S., Innovate UK, June 2014-November 2014). Data coming from UK Environment Agency, IPPC Directive and Waste Interrogator has been used in the project in order to identify waste streams with the potential to be low-cost, and low-carbon, alternative raw materials (ARM) for major infrastructure projects. Sectors involved: Construction and non-construction industry, plastics, food. Objectives: This project identified far higher availability of ARMS across other (non-construction) sectors of the economy than had been envisaged. Meaningful outcomes: The project found that 700,000 tonnes of construction and demolition waste was being recovered for reuse within the industry each year. However, a potential of over 17 million tonnes of alternative raw materials generated each year that was available for reuse by the construction industry have been identified.

International Best Practice for Industrial Waste Exchange – a Roadmap (InternationalBestPractices, Egyptian National Cleaner Production Centre (ENCPC), April 2015-May 2015). The project informed the development of a national integrated Industrial Waste Exchange (IWEX) programme in Egypt by examining international best practice for IWEX in 3 chosen countries (UK, South Africa and Turkey). The recommendation for IWEX taking into account Egyptian context was a facilitated industrial symbiosis model supported by public/institutional investment which is being used today. The project illustrates how to effectively engage with stakeholders for the effective production and implementation of industrial symbiosis roadmaps. Objectives: The main aim of this report is to demonstrate the most effective methods of identifying waste resources and where they can be used as input for other product or services.

FIRECE (FIRECE, Interreg Central EU, 2017-2020). The main objective of FIRECE is to increase capacities of regional operator to manage Energy Plans particularly on the financial resources locally available to enhance the investments in renewable energy (RE)by Industry, especially SMEs. The focus is on setting up Innovative Financial Instruments (IFIs) that will act as a leverage of the public resources available by Regional Authorities in charge to manage EU funds(Managing Authorities-MA). In parallel, a quality assessment criteria will assist operators and local actors to check and optimize use of public resources addressed to investments on RE by the industrial sectors(manufacturing). The main project outputs are a transnational strategy to implement financial schemes and assess investments by public resources for Industry, a strong exchange knowledge action addressed to regional operators with training courses organized in 9 different regions, a methodology to support the exploitation of financial common financial schemes identified and a tool on-line available to local actors for the quality assessment of the investments. The project will implement 2 pilot actions in 9 different regions: 6 regions will develop ex-ante analysis and following feasibilities study for IFIs to be included in current or new ERDF Programming period; 5 regions will test the tool to assess projects and investments supported by public resources in the frame of the Regional Energy Plans. A strong transferability action will assure dissemination of outputs and their sustainability. The areas participating in the project vary greatly in their financial support to RE market, so FIRECE project approach would encourage mutual learning and cooperation. Sectors involved: SMEs and financial institutions. Objectives: The project aims at improving the capacities of the public sector and related entities to plan territorially based low-carbon strategies in the frame of Regional Energy plans, supporting the low-carbon energy transition of traditional industrial sector to meet the regional energy saving targets defined according to EU and national legislation. The objective will be achieve supporting Regional Authorities, Energy Agencies and Regional Financial Agencies to elaborate and implement innovative financial instruments(IFIs) particularly addressed to provide Energy savings investments and project plans elaborated by SMEs. In parallel, an assessment procedure will check the quality of the investments and projects elaborated by SMEs to optimize resources and reach the targets. FIRECE project links to the specific objective because it will support public sector to plan and manage instruments able to achieve saving targets. The implementation of Innovative financial instruments and the assessment of the projects submitted by SMEs for energy savings will contribute to achieve the indicators contained in the Regional Energy Plans. Finally, FIRECE contributes to the achievements of the energy saving targets planned at worldwide and EU level. Meaningful outcomes:

- Contribute to the implementation of the Regional Energy Plans and to achieve the targets (in terms of Energy savngs and RES) planned at EU and National Level;
- Testing innovative financial mechanisms for energy efficiency measures designed especially for SMEs. Enterprises will be assisted to apply to the innovative financial instruments with assessed investment plans, improving their capacity to meet Energy savings and RES targets according to their Regional Energy Plans;
- Pilot actions and ex-ante assessment analyses will permit to define the best Financial Instruments to reach the required energy saving.

REMOVAL (REMOVAL, H2020, 2018-2022). The RemovAL project will combine, optimize and scale-up developed processing technologies for extracting base and critical metals from such industrial residues and valorising the remaining processing residues in the construction sector. The ambition of RemovAL is straightforward: to overcome environmental issues and technological barriers related to aluminium industry, by combining and advancing existing technologies for the sustainable processing of BR, SPL and other by-products, generating revenue in symbiosis with other industrial sectors. RemovAL optimizes and arranges technological innovations into new industrial processes-flowsheets. Swift scale-up is ensured by using mature industrial reactor technologies (Electric Arc Furnace, Rotary Kiln, …) to convert BR into products that are directly marketable (blended OPC, mineral wool, aggregates, building blocks and panels and others) or directly integrated in the existing processing scenarios of crucial industrial sectors like ferro-alloy, cement, construction materials and others. Sectors involved: Alumina, Steel, Construction, Chemical. Objectives: In RemovAL, 6 innovative pilot plants will be run. Combined they will form a network of technological nodes, enabling optimum processing flow sheets for valorising the produced Bauxite Residue (BR) from alumina refineries along with other industrial by-products like Spent Pot Lining (SPL) from aluminium smelters. These technologies can then be adjusted to suit all kind of BR compositions around Europe. The validation will be done for 3 European alumina producers (represeanting 44% of the European alumina production) and one legacy site owner, present in the consortium. Meaningful outcomes: Deliver and validate a complete feasibility study for each of the 3 alumina producers and the 1 legacy site owner in the consortium detailing the optimum processing flow sheet for valorising the produced Bauxite Residue (BR) along with other industrial by-products, taking into consideration waste characteristics, logistics and potential for symbiosis with other plants in the geographical vicinity. Following this, each plant will be able to implement its own BR valorisation plan.

SCALE (SCALE, H2020, 2016-2021). Sectors involved: Alumina, Chemical. Objectives: To demonstrate a novel value chain for production of Sc and Al-Sc alloys from European secondary resources. The SCALE project develops the technology to extract Scandium from Bauxite Residue and upgrade it to commercial product, setting the foundation for multilevel valorization of BR leading to a zero-waste solution. The SCALE project develops the technology to extract Scandium from TiO2 by-products and upgrade it to commercial product, setting the foundation for an additional European Sc-resource. SCALE develops new technological routes, by-passing existing expensive (and in some cases potentially dangerous for the human health) processing steps like Sc fluorination (IV) from ultra-pure Sc2O3 with gaseous HFor Sc reduction through calciothermic reduction of ScF3 (V) and Sc-Al alloying from metallic Sc (VI). New connections in the processing chain are established through innovative SCALE technologies, which allow direct crystallization of ScF3 from Sc strip solution, direct electrolysis of Sc2O3, and direct production of Sc-Al master alloy from Sc2O3 or ScF3. Meaningful outcomes: Industrial Pilot scale demonstration for Sc extraction from Bauxite Residue and Acid Waste.

ENERGEIA (ENERGEIA, Interreg Med Programme, 2011-2013). This project was born in order to support start-up companies in the industry of renewable energy. Best practices in the Renewable Energy Sector (RES) have been detected and they can be transferred from one region to another within the project. The creation of a favorable environment for the development of new enterprises and to the strengthening of the existing ones, for example by examining the new market rules, the opportunities offered by European research programs and the synergies developable thanks to networking actions have been organized. Objectives: The main aim was to design a strategy able to develop tools and practices in order to support the renewable energy entrepreneurship in partner regions. Meaningful outcomes: Pilot actions have been designed and implemented. This project developed tools, networks and cooperation methodologies ready to meet the challenges of supporting innovative nascent businesses raising from research outputs and competences.

INCUBIS (INCUBIS, Grant agreement ID: 894800, H2020-EU.3.3.1. - Reducing energy consumption and carbon foorpint by smart and sustainable use, 2020-2023). Objectives: INCUBIS aims to decarbonise European industry by 2050 by unlocking the market potential of ENERGY SYMBIOSIS through developing and deploying 5 Energy Symbiosis Incubators across Europe, complemented by a digital Cloud Incubator, thus enabling the utilization of waste energy from EEIs. INCUBIS will achieve total energy saving, generate benefits, achieve GHG reduction, and convince business over 40 industrial parks to commit to energy cooperation.

Study and portfolio review of the projects on industrial symbiosis in DG Research and Innovation (Sommer K. H., Directorate-General for Research and Innovation (European Commission), 2020-03-09). This study assesses a portfolio of 28 EU funded projects on IS, as well as pratical experiences from two industrial sites. It also analyses technological and non-technological factors for implementing IS. In this context, digital technologies are considered key technological building blocks in managing complex cross-sectoral and multi-actor operations, as well as in safeguarding data integrity and confidentiality. The study introduces the concept of symbiosis readiness level (SRL) as well as the importance of facilitation mechanisms and actors in establishing the required cross-sectoral cooperation leading to IS implementation. The recommendations of the study include to: establish a community-of-practice to identify, collect and disseminate best practices in IS; identify the potential for industrial urban symbiosis via circularity hubs proposed by industry, the establishment of an open data source information exchange platform for IS; increase in R&I-funding to foster implementation of IS.

CORALIS (CORALIS, H2020, under the agreement n. 958337; 2020-2023) “Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis” project involves all SPIRE sectors. The CORALIS project seeks to demonstrate applicable solutions for Industrial Symbiosis aiming at energy and resources savings, in the framework of sustainability and CE. The main objective of CORALIS is to create pathways for the decarbonisation of resource and energy intensive sector value chains through the implementation of viable IS approaches combining new business and management strategies with innovative technology-based enablers. CORALIS has been designed as a demonstration project for the generation of real experiences on the deployment of IS solutions and the overcoming of the barriers faced by these initiatives. Objectives: The main objective of CORALIS is to create pathways for the decarbonisation of resource and energy intensive sector value chains through the implementation of viable IS approaches combining new business and management strategies with innovative technology-based enablers. The overall approach of CORALIS will be demonstrated in a total of 3 industrial parks, each of them supported by an IS facilitator, a neutral actor in charge of guiding the IS initiative and exploiting its full potential. Further replication is expected by gathering the project results in CORALIS Handbook for supporting the implementation of IS, by providing recommendations on regulation and standardization and by establishing a continuous dialogue with main European stakeholders following an ambitious dissemination and exploitation strategy. Results: An innovative output that is expected from the project is the development of a Virtual Assessment Platform for Industrial Symbiosis operation for the application to a real industrial environment. This impact assessment methodology will be implemented into a virtual assessment platform that will support the operation of the involved industrial parks. 3 additional industrial parks will follow the project results in order to replicate them by implementing additional IS initiatives after the project’s end.

STEELANOL (STEELANOL, H2020-EU.3.3.-SOCIETAL CHALLENGES-Secure, clean and efficient energy; 01/05/2015-31/03/2024) “Production of sustainable, advanced bio-ethANOL through an innovative gas-fermentation process using exhaust gases emitted in the STEEL industry” concerns technological solutions, to utilize process gases from the iron and steel industry for production of fuels and chemicals, are an attractive sustainable and economic approach for industries today. This innovative approach converts carbon and hydrogen-rich off-gases, such as coke oven gas, blast furnace top gas and also converter gas into liquid based energy sources through a biological gas fermentation process to produce preferably ethanol or other chemicals. To produce ethanol, an integrated fermentation system with additional downstream installations is required to treat the fermentation product and waste streams.

Objectives: to convert CO_2 into valuable chemical useful for other industrial sectors. Meaningful outcomes: gas fermentation offers a new route to create value from iron and steelmaking off-gases while also meeting requirements to reduce GHG emissions. Additionally, the flexibility of gas fermentation will enable production of a wider range of chemicals over time, creating additional value for the iron and steel industry and deepening connections with the chemicals industry.

R3VOLUTION (R3VOLUTION, HORIZON-CL4-2023-TWIN-TRANSITION-01;01/01/2024-31/12/2027) "A rEVOLUTIONary approach for maximising process water REuse and RE-source REcovery through a smart, circular and integrated solution" project will revolutionize industrial water management in the EU, providing key innovations that can enable economically, environmentally and operationally water reclamation projects (by addressing solutes and energy recovery challenges), and generate significant impact for the EU in the next decade. To pave the way towards sustainable and efficient water and resource consumption, R3V takes on the challenge of developing and demonstrating a resource recovery solution that will enable >90% water reuse across most intensive water industries, applicable upstream and downstream, whilst recovering >45% effluents solutes, >50% waste heat reuse and eliminate 100% of hazardous substances. R3V will investigate, develop and demonstrate tailored membrane-based treatment trains coupled with waste heat, and a digital process assistant (DPA) to support the design phase to achieve optimal configuration for different industrial settings, minimising risks in implementation and provide critical support in operation. Objectives: with the aim to demonstrate R3V solution capabilities and replicability potential across varied process industries, the project includes 4 physical demo cases at pilot scale targeting several up- and down- streams in a variety of industries with high water discharges and complex effluents: petrochemical, bio-based chemical, pulp & paper and steel, each led by renowned technological partners. The project will also assess the transferability of the results by evaluating one additional industry (mining in Chile), and its replicability in 3 additional streams, via the DPA tool developed within the project.

ICARUS (ICARUS, HORIZON.2.4 - Digital, Industry and Space; 01/01/2024 - 31/12/2027) will upcycle waste material resources of most selected process industries (covering minerals, cement, ceramic, non-ferrous metals, steel, water, pulp & paper and chemical ones) to achieve circular and sustainable process industries overcoming their final application in construction sector. This project will accelerate the process industry uptake and contribute towards the developed education and skills activities and outcomes in this area as well as linking all value chain from industrial players recyclers, public authorities, and standardisation actors. ICARUS tackles resources usage in the construction sector (housing and infrastructure), accounting for 50% of the total material extraction, and being responsible for more than 35% of waste streams in the EU. Furthermore, the CE in the sector is still at a very early stage, with an estimated level of circularity for the EU of 12.4% material use rate in the year 2021. Objectives: ICARUS approach aims to give technological support to stakeholders of energy-intensive and construction industries as key players for the transition to a more green and digital processes industries supported by standardization aspects to promote values and a resilient, green and digital Single Market and business models including co-creation and co-design to successful market implementation. ICARUS will represent a breakthrough in the research and demonstration of new technologies to upgrade Secondary Raw Materials, ensuring similar quality as primary raw materials of three waste streams to improve CE principles in several intensive industries with its implementation in the construction sector, to improve CE principles in P4P process industries. These new technologies will be demonstrated throughout 3 demo cases: 1. Upcycling of

Lithium Aluminosilicate Residue; 2. Upcycling of SRMs from urban waste cellulose; 3. Upcycling of steelmaking slags via Carbon Capture and Storage.

CORNERSTONE (CORNERSTONE, Horizon.2.4-Digital, Industry and Space; 01/01/2024-31/12/2027). Europe aims to achieve climate neutrality and CE by 2050. To reach this goal, current industrial wastewater treatment processes must be aligned to meet the EU's ambitions regarding climate and sustainability. Objectives: CORNERSTONE project aims to integrate innovative processes, smart monitoring, and new digital solutions into existing industrial wastewater treatment practices to recycle freshwater, energy and solutes from industrial effluents. The project targets the steel, pulp & paper, and chemical industries to showcase the potential of the advanced wastewater systems developed within its framework. These industries are essential in realising the objectives of the P4Planet partnership, which aim to transform European process industries, make them circular, achieve overall climate neutrality at the EU level by 2050 and enhance their global competitiveness.

RESURGENCE (RESURGENCE, Horizon.2.4-Digital, Industry and Space; 01/12/2023-30/11/2027) project aims to research industrial water circularity and previous and current solutions for addressing these challenges. It will then work to develop novel, more efficient industrial circular water systems that could benefit not only climate neutrality goals, but also competitiveness. The project will operate on four case studies in different industrial sectors, testing innovative solutions with the help of experts and specialists from 11 countries. Objectives: RESURGENCE addresses industrial circular water systems in a wide perspective which embraces efficient technologies for water circularity, energy and feedstock recovery, with the aim of contributing to EU climate neutrality, circularity, and competitiveness. RESURGENCE will work in 4 case studies that include 3 industrial sectors – Pulp & Paper, Chemical and Steel – as well as a 4th case to explore the synergies between urban water treatment and industries. Meaningful outcomes: innovative solutions will be tested for water treatment – membranes, electrochemical technologies, adsorbents, advanced oxidation processes and hybrid biological systems – exploring also the recovery of energy (heat, electricity, biogas, H_2) and feedstocks (bioactive fenols, biopolymers, cellulose, lignin, latex, acrylic polymers, phosphate & nitrogen, biochar, MOFs and metals, including Critical Raw Materials). Digital tools will be also developed and applied, including models for energy, water and risk management, physical and software sensors for data acquisition, digital twins, and decision-support tools enabling optimal water treatment technology set-up and day-to-day operation with seized flexibility opportunities on smart grids. The project will be guided by a comprehensive sustainability and economic assessment to support by evidence the gains of these technologies, together with H&S analysis. Local effects multiplication of case studies is pursued by promoting seeds of future hubs for circularity.

FLEXIndustries (FLEXIndustries, Horizon.2.4-Digital, Industry and Space; 01/06/2022-31/05/2026) builds upon a holistic multi-disciplinary (device, process and value-chain) and multi-scale (operating, tactical and strategic) approach fostering its 7 multi-sector (automotive, biofuels, polymers, steel, pulp & paper, pharmaceuticals, cement) energy intensive industries design and deploy the most suitable Energy Efficiency Measures and Process Flexibility Methods for their industrial environments along with a positive impact onto their interconnection with the electrical & heating networks. Objectives: FLEXIndustries develops and demonstrates a Dynamic Energy & Process Management Platform to monitor, analyse and optimize the most energy-intensive industrial processes, by managing properly emerging demand response mechanisms and providing plant and process flexibility as well as offering grid services. The unique premise of FLEXIndustries, is the optimal integration of i) innovative energy generation, storage and conversion assets (e.g. BESS and waste heat recovery solutions based on novel HPs, ORC and thermoelectric systems), ii) smart and digital tools for optimised operation and control, all supported by iii) novel business models and market mechanisms for enhanced industrial flexibility. Meaningful outcomes: overall, FLEXIndustries has the potential to save: a) ≥ 159 GWh/ y of Primary Energy in total, b) ≥ 6.0 M€/y Life Cycle Costs on demo scale and c) ≥ 33,111 CO2-eq/y emissions at project level. Demonstration will take place in 7 industrial facilities in 6 reference countries (Turkey, Greece, Poland, Bulgaria, Germany and Italy) and will feature: a) energy efficiency and operational flexibility along with process redesign/modification, b) increased levels of electrification, digitalisation and automation, c) enhanced user satisfaction and grid flexibility services, and d) decreased environmental footprint.

HyInHeat (HyInHeat, Horizon.2.4-Digital, Industry and Space; 01/01/2023-31/12/2026) project aims to integrate hydrogen as a fuel for high-temperature industrial heating processes through efficient hydrogen combustion systems in the aluminium and steel sectors. The project will redesign and modify the heating process itself, supported by simulation methods enhancing digitalisation along the value chain to increase energy efficiency and reduce the future hydrogen demand of the processes. HyInHeat will implement the developed technology in eight demonstrations in technical centres and industrial plants and perform test trials complemented by industrial case studies. Objectives: the main objective of HyInHeat is the integration of hydrogen as fuel for high temperature heating processes in the EIIs. While some of the equipment is already presented as hydrogen-ready, the integration of hydrogen combustion in heating processes still needs adoption and redesign of infrastructure, equipment and the process itself. HyInHeat realizes the implementation of efficient hydrogen combustion systems to decarbonize heating and melting processes of the aluminium and steel sectors, covering almost their complete process chains. To reach this overarching objective within the project, furnace and equipment like burners or measurement and control technology but also infrastructure is redesigned, modified and implemented in eight demonstrators at technical centres and industrial plants. Besides hydrogen-air heating, oxygen-enriched combustion and hydrogen-oxyfuel heating is implemented to boost energy efficiency and to decrease the future hydrogen fuel demand of the processes. This might result in a total redesign of the heating process itself which will be supported by simulation methods enhancing digitalisation along the value chain. With these activities, HyInHeat contributes to the objectives of decreasing CO_2 emission of the processes while increasing energy efficiency in a cost competitive way keeping NO_x emission levels and resource efficiency at least at the same level.

CUMERI (CUMERI, HORIZON-CL4-2022-RESILIENCE-01; 01/12/2022-30/11/2025) project will develop and demonstrate advanced membrane separation systems customised for the steel and oil and gas (O&G) sectors. In the steel sector, one comprehensive system will both recover H_2 and capture CO_2. The O&G industry will benefit from a two-step liquid filtration system to recover base oil and additives recovery from used lubricant oil. The technologies will decrease emissions, enhance the valorisation of valuable chemicals, and increase energy efficiency while promoting a circular economy. Objectives: the CUMERI project will develop and demonstrate at TRL7 advanced and customised membrane separation systems in two key industries: in the steel sector where H_2 will be recovered and CO_2 captured in one comprehensive system, and in the O&G industry where a two-step liquid filtration system will enable base oil and additives recovery from used lubricant oil. To reach these goals, CUMERI will elaborate three impactful membrane technologies: 1) Enhanced bio-based and recyclable polymer membranes for CO_2 permeation; 2) Stable and selective SiC/SiCN membranes for H_2 recovery, for a better H_2 valorisation in the steel sector; 3) Grafted porous ceramic membranes for waste oil purification and additives recovery by ultra-filtration and liquid-liquid membrane contactors. All membrane systems will unlock greater energy efficiency and decreased emissions in their respective sectors. High separation performances together with increased chemical, mechanical and thermal stability will be demonstrated. Moreover, re-usage and recycling of membranes will be validated. Beyond these demonstrations, the project will generate novel insights on membrane separation including a variety of flexible solutions to help industry, the scientific community and policy makers accelerate the rollout of separation technologies. To maximise the impact of CUMERI, other promising separations will be screened and the transferability of results to other industries (refinery, pharmaceuticals, etc.) will be ensured. Through its activities, CUMERI will pave the way to decreased emissions in the industry, to the greater valorisation of valuable chemicals, and to more energy-efficient processes, promoting resilient and circular industrial value chains.

CAPTUS (CAPTUS, HORIZON-CL5-2022-D3-02-05; 01/06/2023-31/05/2027) project aims to make EII-derived CO_2 an exploitable resource through the industrial demonstration of three promising CCU technologies, where the CO_2 captured from cement, steel, and chemical plants will be valorised into different RE carriers. The CAPTUS processes involve the integration of surplus RE, contributing to a more efficient and sustainable transition and including detailed analyses on safety, environmental, societal, and business aspects. Objectives: CAPTUS key objective is to demonstrate sustainable, cost-effective and scalable pathways to produce high-added value energy carriers by valorising industrial carbon emissions and integrating renewable electricity surplus. To this end, 3 complete value chains will be demonstrated at 3 different demo-sites: (i) Bioprocess based on a two-stage fermentation to produce triglycerides in a steel plant, (ii) Lipids-rich microalgae cultivation followed by hydrothermal liquefaction to produce bio-oils in a chemical plant, and (iii) Electrochemical reduction of CO_2 to produce formic acid in a cement plant. The proposed technologies will be tested at TRL7, and the obtained energy carriers will be validated by upgrading studies. CAPTUS will also validate solutions regarding economic, environmental, societal and geo-political criteria, contributing to the development of novel business models, guidelines and strategies. Overall, CAPTUS innovations at technical, economical, managerial and social level will enable the consolidation of CCU technologies within 3 EII key sectors and leverage their benefits by reducing carbon emissions, increasing renewables share and producing valuable energy carriers.

VALORISH (VALORISH, Horizon Europe; 01/05/2024-31/10/2027) project, developing bioproducts by using residues from fishing industry, will enhance the sustainability of natural resources management (in line with Key Strategic Orientation-KSO B). The project will create more sustainable bio-based processes and products, reducing the environmental impact and progressing in marine biotechnology (aligned with KSO C). Moreover, to prevent managing waste and by-products of fishing industry as Animal By-Products (ABP) of category 3 (Regulation (EC) No 1069/2009), for which the valorisation routes result in low value (e.g., silage, compost or biogas production) or directly disposed (e.g., incineration, co-incineration or landfilling), will reduce significant CO_2 emissions, thus enhancing climate neutrality. VALORISH aims to develop a novel computationally-assisted methodology for guiding the design and implementation of a cascade biorefinery approach to valorise waste and by-products of fishing industry through the extraction and bioproduction of high-value bioproducts, targeting applications as nutraceuticals, food supplements, bacteriocins and antigens. Objectives: Optimization of fish oil extraction employing different techniques with low environmental impact; Optimization of protein hydrolysis by fermentation, as a safe and efficient process; Optimal production of high-value bioproducts using fish protein hydrolysates (FPH) as substrate for microbial growth and metabolite production; Employment of the fish oil, protein hydrolysates and the high value bioproducts as nutraceuticals, food supplements, bacteriocins, and antigens whose activity, quality, and safety properties are assessed; Minimization of the biorefinery residues in a zero-waste goal; Application of computational tools to design, optimize, validate and scale-up the processes of the biorefinery.

RISERS (RISERS, Horizon Europe; 01/01/2024-31/12/2026) project addresses developing a roadmap that defines areas, directions and proposes actions where standards are needed to advance IS with focus on priority resources and synergies demonstrating the highest symbiotic potential in Europe. IS refers to collaborative and mutually profitable relationships between different industries and/or sectors to improve resource utilization and productivity based on business opportunities. It creates an interconnected industrial landscape where one company or sector uses underutilised resources such as: as waste, by-products, residues, energy, water, infrastructures, capacity, expertise, equipment, materials from another company or sector with the result of keeping resources in productive use for longer and for an economic profit. This three-year initiative will pave the way to develop standards that support building symbiotic collaborations among industries and sectors that allow keeping resources in productive use for longer. Objectives: to develop a roadmap that defines areas and directions and propose actions where standards are needed to advance IS with focus on priority resources and synergies. Key activities of the RISERS project involve: identification of priority synergies between industries and sectors together with resources most relevant for IS, strengthening the links between R&I and standardisation to valorise and integrate R&I results into IS standardisation processes, cooperation with policy makers to develop policy frameworks in support of industrial symbiosis and engagement with standardisation experts to develop a Standardisation Roadmap for boosting IS impact complemented with guidelines for technical committees to address industrial symbiosis in standardisation processes. Meaningful outcomes: the project capitalises on the Workshop Agreement (CWA 17354) ‘Industrial Symbiosis: Core Elements and Implementation Approaches’ published by the European Committee for Standardisation (CEN). It provides a consensus on the core elements of IS to enable its identification and on good practice approaches to implementation across Europe and beyond.

4 Industrial Symbiosis across sectors

IS refers to establishing multidimensional synergies across different industries. These synergies can be economical, social, or environmental. The economic synergies result from the production of marketplaces for underused resources resulting in revenues and cost savings. The social impact often refers to jobs generation and to promoting relationships with communities surrounding industries. This is particularly relevant for urban IS, mainly related to infrastructure needs of urban areas and more specifically to energy and material flows (Ažman Momirski , Mušič, B., & Cotič, 2021). Concerning the environmental aspects, the synergy is mainly focused on material and emissions efficiencies promoting resource conservation and reducing associated environmental impacts (Axelson, Oberthür, & Nilsson, 2021).

In order to achieve their transition towards a CE in Europe, the cross-sectorial IS is potential pathway for the EIIs. In this context, waste, energy, by-products and water are the most prevalent streams being exchanged among different industries, such as chemicals, steel, and cement sector. Chemicals as a resource sink primarily enables energy and waste synergies, while as a source, the sector enables primarily by-products and energy synergies as the chemical sector has wide range of applications. Concerning the steel sector mostly has a source role to build waste and energy synergies, while as a sink, this sector enables waste and energy synergies. On the other hand, the cement sector tends to predominantly act as a sink developing waste synergies, while as a source, it enables energy and waste synergies. The technology insights cover a collection of technologies for energy, waste, by-product, and water synergies.

4.1 Iron and Steel Sector

4.1.1 State of the art of the industrial symbiosis in the Steel Sector

The European steel sector accounted for 10% of the total world output (metric tonnes of steel) in 2019 (EUROFER, 2020). As steel is fundamental for the manufacturing and the construction industry, this implies a high demand for raw materials and, consequently, high amounts of emissions. The input of the steel industry is about two tonnes of material, such as iron ore and coke, to produce one tonne of steel (Worldsteel, 2019). The total industrial CO_2 emissions in 2018 from the steel sector made up for 22% of the total industrial CO_2 emissions in the EU ETS (de Bruyn, Jongsma, Kampman, G¨orlach, & Thie, 2020). The EU steel industry currently accounts for 221 Mt GHG emissions per year, that include both direct and indirect emissions and represents the 5.7% of total EU emissions. Although the EU steel industry has already reduced emissions by 26% since 1990, due to EE improvements and higher recycling rates, it is committed to reduce its CO_2 emissions by up to 50% by 2030 compared to 1990s level. Over the last few decades, the steel sector has been committed to build a research and innovation framework in order to develop key low-carbon technologies (decarbonization process). In addition, the use of low-carbon energy at globally competitive prices is a priority for the transition of the steel industry. On the other hand, effective policy measures can lead to European low-carbon industrial production competitive on internal and global markets (Peters K., 2019). Over the last few decades, the steel sector has been committed to develop IS activities that aim at reducing dependence on critical materials and replacing virgin materials, resulting also in CO_2 emissions mitigation and innovative technologies development to transform existing resources in the value chain into a usable form. In this context, the most important EIIs closely linked to the steel industry, such as cement, ceramics (including refractory), chemical, nonferrous, or refining, can benefit from IS approaches. The different synergies between different sectors can result in greater skills, jobs and open up new markets, including for low-carbon steel, hydrogen, alternative fuels and feedstocks for the chemical industry, enhancing the circular economy as well as the IS.

Steel is produced by two main routes: the iron ore-based steelmaking and the scrap-based steelmaking. The first route, based on Blast Furnace (BF), where iron ore is reduced to hot metal and then converted into steel in the Basic Oxygen Furnace (BOF), produces about the 70% of the world steel. The second route, based on the Electric Arc Furnace (EAF), using scrap steel as input as well as electricity as energy source, produces about the 28% of the world steel. The remaining 2% is produced mainly with Direct Reduction Plants. At European level the production share between the two main production route is 58% by BF route and 42% by EAF route.

According to the principles of Circular Economy the steel sector is committed to achieve the “zero-waste” goal (Yang, Chuang, & Huang, 2017), based on the 4 “R” (Ansari, 2017): Reduce (minimization of the environmental impact), Reuse (internal reuse of by-products and energy), Recycle (by-products and energy from one sector can be valuable inputs to other sectors, according to the IS concept (Lombardi & Laybourn, 2012)) and Restore (reduction of the impact of steel products). Although these practices have been consolidated in the steel sector, further improvements can be achieved (Rossetti di Valdalbero, 2017) with potential internal and external uses of by-products. Significant examples of IS implementation involving the steel sector have been recently provided, taken into account a series of alternate uses for the waste energy and the material waste and by-products (Fullana Puig, 2019) (Branca, et al., 2020). In particular, waste and by-products coming from different sectors can be valorized as Thermal Energy Storage (TES) materials (Gutierrez, et al., 2016).

Among iron and steelmaking by-products, **slags** are produced in largest quantities. Their formation occur during melting and refining processes, such as BF, BOF, EAF, Ladle Furnace (LF), where fluxes, such as limestone, dolomite, silica sand, are added. The main slag components are silica, calcium oxide, magnesium oxide, aluminium and iron oxides. During iron and steelmaking refining processes the slags, floating over the metal surface, remove impurities present in iron ore, scrap, etc., and protect the liquid metal from oxygen by also maintaining temperature inside the furnace. Steelmaking slags, coming from BOF, EAF and LF are currently recovered over 80% (Di Sante, Cirilli, & Angelucci, 2013) while ironmaking slag, coming from BF, to nearly 100%. The knowledge of the slags composition and, consequently, their volume instability and their leaching behavior (Fisher & Barron, 2019), helps to make them suitable for reuse and/or inert disposal (Branca, Colla, & Valentini, 2009). BF slag is mainly reused in cement production, while in some steelworks BOF slag is landfilled. Among new potential uses of BF slag, the most significant are: foundation material for road and railway construction, lightweight marine embankments, water treatment and glass manufacture. On the other hand, the use of BOF's slag has increased as it can be also used as fertilizer, concrete aggregate and road paving. In addition, depending on the slag composition, bioleaching can be used for **recovering metals**, such as aluminium (Al), chromium (Cr) and vanadium (V) (Gomes, Funari, Mayes, Rogerson, & Prior, 2018). On the other hand, steel slags can be applied for removing elements harmful to the environmental, such as Cr(VI) ions (hexavalent chromium) (Baalamurugan, et al., 2018), Cd (II) and Mn(II) (El-Azim, Seleman, & Saad, 2019), from aqueous solution. In addition, BF slag, dust from the bag filters in the coking installation and dust from the liquid sludge from the scrubber, can be used in removing tricholoroethylene (TCE) from the groundwater, for instance using hydrogen peroxide (Gonzalez-Olmos, et al., 2018).

Furthermore, BF and steel slags can be used for **heat recovery** by applying different methods (Sun, Zhang, Liu, & Wang, 2015) (McDonald & Werner, 2014) and also as energy storage material in Thermal Energy Storage (TES) systems (Oge, Ozkan, Celik, Gok, & Karaoglanli, 2019). In addition, further EAF applications include its recycling as a green source in **ceramic tile** production and also in the **biomedical applications**, due to the bioactivity and biocompatibility of Fluorapatite-based glass ceramics for some applications (e.g. bone replacement, dental and orthopaedic applications (Grillo, Coleti, Espinosa, Oliveira, & Tenório, 2014).

Other iron and steelmaking by-products are represented by **dusts** and **sludges**. Sludges, containing high moisture, come from dust or fines in several processes. After removal from the gases, dust and sludges containing iron oxides and carbon can be internally recycled (Grillo, Coleti, Espinosa, Oliveira, & Tenório, 2014) as well as reused by other sectors, for instance, for Portland cement production. In particular, sludge can be internally used as raw material for zinc ingots, used for producing wire rod in the galvanising process, consisting in prevent corrosion by coating the wire with zinc (Sellitto & Murakami, 2018). Innovative technological approaches can be applied for Zn recovery from EAF dust in order to be used in different applications (Jorge, 2015). In particular, some examples can be provided by ultrasound-assisted leaching process (Brunelli & Dabalà, 2015), by using microwave heating oven as a heat source (Omran, Fabritius, & Heikkinen, 2019), zinc recovery from the pre-treatment of coated steel scrap (Porzio G. , et al., 2016). Furthermore, selective leaching tests have been performed to recover pure zinc compounds or metallic zinc from EAF secondary steelmaking by-products (Varga, Bokányi, & Török, 2016). In addition, it has been recently studied the high-zinc fraction from BF sludge to be possibly incorporated in self-reducing cold-bonded briquettes and pellets (Andersson, et al., 2018), and some valuable metals can be recovered from other by-products (Davydenko, Karasev, Glaser, & Jönsson, 2019).

Fly ashes from steelmaking are mainly used for producing cement and concrete. They could be used in the production of fly ash bricks as well as glass-ceramic products. In particular, fly ash, microsilica, and quartz mixtures can be used for ceramics sintering (He, et al., 2018). On the other hand, fly ash can also be used to improve the structural quality of soil, on road engineering and as a soil fertilizer, due to its high concentration of K, Na, Zn, Fe, Ca and Mg.

Mill-scale is produced during the continuous casting and rolling mill processes in oxidising atmosphere, due to iron oxides layer formation in the surface of steel. It can potentially be used for producing pellets and briquettes for other steelworks as well as to produce magnetic ferrite spinel, used to produce magnets. Furthermore, its minor uses include the addition to casting sands to avoid porosity defect formation as well as the production of pigments for paints, plastics, cosmetics, and cements, also glass making. **Refractory** residues can be reused as roadbed material, slag conditioners directly inside the steel factory or for producing new refractory material. **Iron- and steelmaking gases**, such as coke oven gas, BF gas and BOF gas, are usually reused after cleaning, both internally and externally, for producing steam and electricity, resulting in between 60% to 100% of the plant power (World Steel, 2014). In particular hydrogen, from coke oven gas, can be used for producing power in a steelworks and ammonium sulphate can be externally used as fertilizer. Finally, the **thermal energy loss** can be recovered in heating, recovering industrial heated wastewater and transfer to deliver hot water for domestic use or in industrial buildings. The recovered thermal energy could be used for producing electricity. The energy recovered could be also used in other energy intensive industries, such as glass, ceramic, oil refining factories and incinerators, resulting in the reduction of fossil fuels use. In addition, waste and by-products coming from different sectors can be valorized as Thermal Energy Storage (TES) materials (Gutierrez, et al., 2016).

The current implementation of IS involving the steel and other sectors, by transactions of by-products and energy, has been proved by recent achievements found in literature. IS represents an opportunity for the steel sector and related industries engaged in raw material and energy supply, technology development and related industries relying on steelmaking by-products (e.g., cement and chemical sectors). Although some residual materials from production processes can be internally recycled, some of them can be better used in other industries. For instance, BTX (benzene, toluene and xylene) can be used in plastic products, and tar and naphthalene for producing electrodes in the aluminium industry, plastics and paints. Iron oxides and slags can be externally used for Portland cement production; and zinc oxides, from the EAF route, can be used as a raw material through the Waelz process (Worldsteel, s.d.). On this subject, some encouraging factors and/or barriers about the use of by-products and residual materials between two or more industries have been identified. They include different factors belonging to different categories, such as physical/technical, regulatory, business, motivation and society ones. In a recent study about residual materials with valuable contents, such as Iron (Fe), carbon (C), and Zinc (Zn) and lime (CaO), have been taken into account

(Rosendahl, et al., 2019). On this subject, it can be concluded that to implement the IS all materials should have the same conditions in order to have the final product with the same properties. In addition, in order to assess the IS possibilities for increasing material efficiency in the steel production, a new methodology has been developed (Lundkvist, et al., 2019). The selected residual materials can allow utilizing valuable contents, such as valuable metals, energy carriers and slag formers, that contributes to reducing the landfilled material amounts, decreasing the raw materials consumption, and reducing their content of undesirable elements, such as sulphur and phosphorous. The analysis has been carried out by combining steel production systems with an economic assessment of the business concepts, based on using residual materials from one industry as secondary raw materials in another. The application of the developed methodology aims at maximizing the secondary materials use and their economic potential. In particular, high economic potential for one material can increase the utilization of other materials with lower economic potential. In addition, the methodology and cost evaluation can be applied to other IS systems. In fact, alongside the technological impact, the economic impact is significant as IS concepts can induce lower OPEX for different industries (reduced financial efforts for primary raw materials, external waste treatment, fossil natural gas, fossil-based electricity, CO_2 emission certificates, etc.). For instance, the economic impact concerning the IS implementation between the steel sector and the zinc industry is related to the use of zinc oxide separated from steelmaking dusts. In particular, fine-coarse BOF dust can contain up to 20 wt.% zinc (Reiter, et al., 2023) and is currently externally treated. By applying a treatment process (e.g., pyrometallurgical) to selectively recover a zinc-rich fraction, this can be used as secondary raw material in zinc industry, saving costs for external dust treatment.

A consolidate example of IS in the steel sector is represented by the slags and other by-products reuse in **cement production**, which has led coping with the increased demand of cement. BF slag rapidly cooled by water quenching, results in a glassy and granular to be used for producing Portland cement. In particular, the Ground Granulated Blast furnace Slag (GGBS) presents structural and durable properties that make it suitable to cement concrete (Saranya, Nagarajan, & Shashikala, 2018). By replacing 50% of cement in mortar with ground GBFS, a compressive strength similar to the reference mortar, containing 100% of cement, can be achieved. In order to reduce the content of harmful wastes, such as H_2S, heavy metals and SO_2 in the slag cooled by water quenching, new methods have been developed, such as dry granulation. Moreover, insoluble chemical activators have been used in order to improve the hydraulic activity of blended slag for Portland cement. Recently, the production of a novel green cement, containing superfine particles with high volume fly ash and BF slag addition, has been developed, resulting in better mechanical properties and better hydration properties (Wu, et al., 2018). Furthermore, suitable aging/weathering and treatments for improving the hydrolyses of free-CaO and MgO can mitigate the instability of steel slags (Jiang, Ling, Shi, & Pan, 2018), in order to make them suitable for using in cement production. In addition, the assessment of the mechanical properties of concrete containing EAF oxidising slag, steel slag, and GBFS has been performed (Lee, 2019) and the improvement of the hydraulic properties of BOF slag, by reducing iron oxides, has been studied (Tsakiridis, Papadimitriou, Tsivilis, & Koroneos, 2008). Furthermore, the potential use of BF flue dust in replacing the traditional fuel and raw materials in cement production has been tested (Baidya, Kumar Ghosh, & Parlikar, 2019), by also applying magnetic separation to reduce the iron content in the flue dust, resulting in advantages for both steel and cement industries. According to the IS concept, further studies have been carried out, by testing other by-products from different sectors (e.g., steel fibre, asphalt, slag, asbestos, lead, dry sludge, wet sludge, fly ash, bagasse ash, red mud, plastic, glass etc.) to be used for concrete preparation (Babita, et al., 2019).

The use of iron steelmaking by-products in **road construction** by replacing conventional natural aggregates has been performed (Xiao, et al., 2019) (Skaf, Pasquini, Revilla-Cuesta, & Ortega-López, 2019), also combining Foundry Sands (FS), EAF steel slags and bottom ash from Municipal SolidWaste Incineration (MSWI) in five different proportions (Pasetto & Baldo, 2018). For instance, recent studies, mainly focused on a zero-waste steel production route, aimed at using the produced slags, dust and refractories as materials useful for civil application, as road construction, saving the utilization of raw materials, as natural basalts (Bianco, Porisiensi, Baracchini, Battigelli, & Ceschia, 2018). This activity permitted to validate the process wastes materials as input road materials for civil application. To reach this target the steel production cycle has been purposely adapted, including also the raw materials pre-treatment and transformation into commercial product (i.e. granella). In addition, steel slag reuse, as a replacement for mineral aggregate, in Hot Mix Asphalt (HMA) has been studied (Nguyen, Lu, & Le, 2018) as well as the EAF steel slag in the asphalt mixture reinforced by aramid fiber (Alnadish & Aman, 2018). Along with steel slags, also BF slag has been recently studied as an alternative substitute of natural crushed aggregate (Alnadish & Aman, 2018). Furthermore, in a recent work the use of BOF slag as coarse aggregate as well as the Blast Furnace Dust (BFD) as a fine aggregate for manufacturing asphalt hot mixes for pavements (López-Díaz, Ochoa-Díaz, & Grimaldo-León, 2018) have been studied.

The use of by-products from the steel sector for **soil amendment** mainly concerns the use of steel slags as a liming material to raise the pH in acidic soils as well as to improve the physical properties of soft soils (Branca, et al., 2014). The application of BOF slag to alkaline sodic soils has been tested in lysimeter trials, resulting in decreasing the exchangeable sodium content of saline sodic soil, irrigated with saline water, and, consequently, in improving the yields, due to the reduction of the negative effect of sodium (Pistocchi, et al., 2017). In addition, by assessing the technical and economic viability of a slag treatment plant, an amendment material to be sold in the fertilizer market can be obtained (Branca, Fornai, Colla, Pistocchi, & Ragaglini, 2019). On the other hand, due to its high porosity and large surface area, steel slags can be used for coral reef repairing (Mohammed, Aa, Ma, & Khm, 2012) and for building artificial reefs as well as for H_2S and metalloids adsorption in marine environments (Asaoka, et al., 2013). Nevertheless, the content of trace amounts of heavy metals in the slags need to be carefully analysed in order to make them suitable for soil amendment. On this subject, BOF slag can reduce the Cr(VI), while adding synthetic $Mn^{IV}O_2$ promotes oxidation of Cr(III). Generally, the oxidation risk of Cr(III) present in BOF slag to Cr(VI), promoted by MnO_2 present in the soil, is very low, because the low solubility of Cr(III) in soil (Reijonen & Hartikainen, 2018). The converter slag is also an amendment material resulting in decreasing the arsenic uptake by rice, probably due to the more Fe-plaque formation adsorbing more arsenic and the competitive inhibition of arsenic uptake with higher availability of Si (Gwon, Khan, Alam, Das, & Kim, 2018). On the other hand, iron materials from the casting industry can immobilize the arsenic in flooded soil, by reducing the arsenic concentration in rice grains (Suda, Yamaguchi, Taniguchi, & Makino, 2018).

Other iron- and steelmaking by-products are currently studied in order to be reused according to the IS concept. Mill scale, formed during the hot rolling process, can be used as Bipolar plates (BPP), a component of Proton Exchange Membrane Fuel Cells (PEMFC) (Khaerudini, et al., 2018). Refractory materials can be internally recycled as slag formers or conditioners or as raw materials in the mixtures for new refractories, resulting in a recycled material to be used for additions to monolithic refractories or for concretes (Madias, 2017). The alliances between steel producers, refractory recyclers and refractory manufacturers paved the way to a circular economy and IS approach (O'Driscoll, 2017) and to the external recycling of refractories in the glass and cement sectors (Fasolini & Martino).

IS also concerns by-products and wastes from other sectors to be used in the steel industry as secondary and recycled materials. On this subject, carbon bearing materials, such as biomass, residues from food companies, plastic and rubber wastes, usually landfilled, represent important materials that can be used to replace fossil materials, such as coal and natural gas. For instance, biomass can be used in steelworks for reducing fossil-based CO_2 emissions (Fick, Mirgaux, Neau, & Patisson, 2014), such as in steelmaking as reducing agent (Suopajärvi, et al., 2018) as well as for replacing Pulverized Coal Injection (PCI) with high carbon content charcoal in cokemaking, sintering and in carbon composite agglomerate production, biomass, especially charcoal. Furthermore, fossil fuels in EAF steelmaking can be replaced with biochar-agglomerates (Kalde, Demus, Echterhof, & Pfeifer, 2015), and the simultaneous conversion and use of carbon dioxide and plastics into fuels/chemicals in high temperature iron and steelmaking can be effective (Devasahayam, 2019). The injection of carbon and charge carbon in EAF with renewable bio-carbon can result in reducing of more than 50% of greenhouse gas emissions (Todoschuk, Giroux, & Ng, 2016). In particular, replacing fossil carbon sources with waste plastics can reduce ~30% of CO_2 emissions (JISF's, 2018).

IS concept implementations are very important to the EU steel sector in order to achieve the climate neutrality, for instance, by using iron-rich secondary material streams being suitable to produce direct reduced and liquid iron for crude steelmaking. However, achieving climate-neutrality by 2050, requires radical changes in production processes. This transformation can be achieved by implementing new steelmaking processes, such as the hydrogen-based steelmaking, by adapting of fossil fuel-based steelmaking through process integration, and by capture and storage or use of waste carbon to produce chemicals. In the steel industry, in order to reduce CO_2 emissions, two main technological pathways, Smart Carbon Usage (SCU) and Carbon Direct Avoidance (CDA), aim at reducing the use of the carbon compared to the current steel production process or at totally avoiding carbon emissions (EUROFER, 2019). Within each pathway different groups of technological approaches are present. In particular, SCU includes: Process integration (PI), Carbon Valorisation or Carbon Capture and Usage (CCU); and CDA includes: Hydrogen-based metallurgy and Electricity-based metallurgy. The current technologies and initiatives concerning the CO_2 mitigation, within the main technology pathways, were recently described (Draxler, Schenk, Bürgler, & Sormann, 2020) (Draxler, et al., 2021), and can be summarised as follows:

- SCU - Process integration pathway
  - Technology routes based on optimised BF-BOF (i.e. Recycling or increased utilization of steel plant gases; Partial replacement of coal by either natural gas, hydrogen injection or biomass (Torero project); Increase of scrap/hot metal ratio, and the replacement of iron ore by hot briquetted iron (HBI).
  - Carbon based smelting reduction (i.e. Iron bath reactor for smelting reduction (HIsarna).
  - Final storage of captured carbon.
- SCU – CCU pathway

CCU aims at bonding CO_2 from steel process and waste gases and using carbon for producing base chemicals. The main CCU projects are as follows: The Steelanol (Steelanol project , s.d.)

and Carbon2Value (Carbon2Value project, s.d.) projects: conversion of the CO and H_2 in the BF gas by using microbes into ethanol; the Carbon2Chem project (Carbon2Chem project, s.d.): methanol production, as well as production of polyalcohols, polymers, and oxymethylene ether (OME); the FresMe project (FresMe project, s.d.): methanol production from steel plant process gases.

- CDA pathway
  - Hydrogen based direct reduction route (H2-DR/EAF route). The direct reduction (DR) process concerns the direct reduction of iron ores with hydrogen shaft furnace processes. In these furnaces the iron ores are reduced in the "dry" stage by CO and H_2 from cracking of natural gas, without liquid phases and slag production. In this context, many European integrated steel plants have already committed to replace the BF route by the H2-DR/EAF route by using natural gas as reductant as long as green hydrogen is not available.
  - Hydrogen plasma smelting reduction is currently investigated on technical scale (SuSteel project , s.d.). Iron electrolysis technologies include alkaline electrolysis (SIDERWIN project, s.d.) and molten oxide electrolysis.

Concerning the by-products production and their recycling and re-use, SCU technologies (including CCU) are not expected to affect both the amount and quality of dusts and sludges production, as BF/BOF process route remains unchanged. However, the application of CDA pathway as the hydrogen-based DR/EAF process route will lead to a different amount and quality of the produced dust, sludge and slag and, consequently, different options of internal recycling of residues. On the other hand, the implementation of the DR/EAF route can result in new dust or sludge from the DR plant and a new kind of EAF dust from the DRI melting step will arise, with different compositions compared to the dusts and sludges from integrated steelmaking and electric steelmaking (e.g. low zinc content). In addition, slag resulted from the DRI melting step will also be different compared to the current BF slag (currently reused in the cement industry). This will imply a suitable adjustment of the new produced EAF slag.

In the future, new opportunities and new synergies and networks with other sectors will be encouraged and developed (Colla, et al., 2023), by taking into account the main drivers, specific barriers and impacts on companies, the environment, and society, considering existing and new networks for new decision-making approaches as well as promoting fruitful new synergies to implement novel solutions and strategies for reducing resource and energy uses and related environmental impacts and investment needs.

The challenge of decarbonisation of the EU steel industry needs a transition process. In this context, IS plays a role as a supporter and accelerator of the transformation of the steel sector and other EIIs to achieve a circular and climate-neutral society.

4.1.2 Projects on Industrial Symbiosis co-funded by the Research Fund for Coal and Steel

In the last 19 years (2005-2024), several RFSR/RFCS European projects related to the Industrial Symbiosis in the steel sector have been funded. Some examples are listed, as follows:

- **SHOCOM** (SHOCOM, RFSR-CT-2005-00001, 01/07/2005-31/12/2008) "Short term CO_2 mitigation for steelmaking". <u>Objectives</u>: To reduce the environmental impact of steelmaking, by reducing greenhouse gas emission, and saving energy and natural resources, through the use of charcoal, the enhancement of coke reactivity, and the use of wastes as reductant for the BF, such as plastic waste. Results: The use of charcoal has a positive effect on coke savings, CO_2 mitigation, but also a significant impact on the BF productivity. Equilibrium modelling showed that utilisation secondary/waste materials led to CO_2 mitigation. The composition of the plastic wastes was a critical factor and the plastic wastes strongly affected the development of coal fluidity, with slight decrease in coke yield.

- **ACASOS** (ACASOS, RCFS-CT-2007-00003; 01/07/2007-31/12/2010) "Alternate carbon sources for sintering of iron ore". Objectives: Investigation of new alternate carbon sources (e.g. olive pits, sunflower husks, BF dust and sludge, anthracite and pet coke) for sinter pot tests and industrial sinter plant trials. Results: Mixtures of carbon containing sludges (BF, BOF) and dusts can be added in the sinter mixture and can only partly substitute carbon breeze. The substitution of coke breeze with 60% anthracite at the industrial scale led to a slight reduction in sinter productivity.
- **URIOM** (URIOM, RCFS-CT- 2007-00010, 01/07/2007-31/12/2010) "Upgrading and Utilisation of Residual Iron Oxide Materials for hot metal production" Objectives: two new technologies for recovery of iron and chromium containing residues from stainless steelmaking, based on modelling results or lab scale and technical scale experiments. Evaluation and comparison of different processes and process variants. Investigation of the following processes: Inductively heated coke bed reactor (ICBR) process and New briquetting technology using vegetable binders to be directly recycled to the EAF. Results: Both the Flash reactor coupled with the ICBR prototype worked fine and the technical concept was capable to process stainless steel EAF dusts. For processing of oxidic residues by a coupled process of cupola furnace and inductively heated coke bed reactor, the electric energy consumption of the coupled process was high. Optimal briquetting process parameters (i.e. forming pressure and humidity content) were defined. No significant chemical differences observed and not significant energy consumption increase, compared to the standard procedure.
- **EPOSS** (EPOSS, RFSR-CT-2007-00006 ; 1/07/2007-31/12/2010) "Energy and productivity optimised EAF stainless steel making by adjusted slag foaming and chemical energy supply " Objectives: To increase the energy efficiency and productivity during EAF high alloyed stainless steelmaking by the development of innovative slag conditioning techniques for slag foaming and adjusted use of all available energy sources. Results: Electric energy consumption decreased, while electric energy saved due the application of an optimised procedure of FeSi addition and carbon/oxygen injection. Chromium reduction achieved for the CaC_2 injection process. Even better Cr reduction for Al injection. Increased productivity for adjusted addition of FeSi and injection of carbon/oxygen.
- **FLEXINJECT** (FLEXINJECT, RFSR-CT-2008-00001; 1/07/2008-31/12/2011) "Flexible injection of alternative carbon material into the blast furnace" Objectives: To reach increased flexibility and use of alternative carbon materials (ACM) such as plastics, dusts, sludges etc. and a sustainable use of carbon resources. Results: industrial conveying trials with PC/BF flue dust mixtures showed that the technical fluidisation and conveying trials were transferable to industrial scale, depending on the layout of the plant. It could be an advantage with a separate system as the risk for damaging the PCI system was minimised. However, the wear will be higher when transporting BF dust only. According to theoretical calculations injection of ACM in mixtures or separately are both feasible methods for implementation on industrial scale. Industrial applications of the tornado process are possible after exploring suitable equipment for

feeding of wet material and material handling of produced dry product fraction. There are no limits in ACM addition to PC up to 25%.

- **SLASORB** (SLASORB, RFSP-CT-2009-00028; 01/07/2009 - 30/06/2012) “Using slag as sorbent to remove phosphorus from wastewater” Objectives: To develop the use of slag in full-scale filters designed to remove phosphorus from wastewaters. Results: Slag can be used as P remover in filters, however filters may vary based on parameters included in the design and operation of the system, the temperature and wastewater composition.
- **GreenEAF** (GreenEAF, RFSR-CT-2009-00004; 01/07/2009 - 30/06/2012) “Sustainable Electric steel production” Objectives: the investigation of the possible partial or total substitution of coal and natural gas with charcoal and syngas produced from pyrolysis of biomass. Results: 1. The optimal temperature (500°C) for biomass pyrolysis to obtain adequate charcoal and syngas. Different types of wood and the agriculture residues were suitable. 2. Use of charcoal as substitute of fossil coal. No relevant effect on the chemistry of metal and slag, except a lower carburization of metal in case of charcoal. Less sulphur level in the molten metal, due to the charcoal use. 3. The use of syngas in partial substitution of natural gas implies the necessity of some modifications of the burners, as the syngas heat produced by syngas lower than that from natural gas.
- **INNOCARB** (INNOCARB, RFSR-CT-2010-00001; 01/07/2010 - 31/12/2013): “Innovative carbon products for substituting coke on BF operation” Objectives: In terms of costs there is a need for further reduction of coke rate due to coke supply situation in Europe. This should be reached by developing two complementary technologies: 1. Substituting coke by means of activated nut coke instead of normal nut coke; 2. Substituting coke by use of briquetted alternative carbon sources (C-bricks). Results: The utilization of carbon bricks from different carbon materials and the replacement of more expensive metallurgical coke at the BF. As carbon materials, low reactive residues from cokery as coke dust or coke breeze as well as pet coke have been identified. The investigations of the carbon brick utilization showed that a coke substitution rate of about 10% with carbon bricks seem to be possible at BF using carbon materials with low reactivity, although the influence of the binder as catalytic agent has to be evaluated. At the experimental BF tests with activated nut coke showed that the C consumed has decreased compared with the reference. The higher energy savings were achieved when using magnetite activated nut coke. The decrease in C consumption was likely due to the reduction of thermal reserve zone temperature with ~25-40 °C. At the lower temperature the equilibrium between Fe/FeO and CO/CO_2 is shifted to higher ratio of Femet at a specific reducing power of the gas.
- **OPTDESLAG** (OPTDESLAG, RFSR-CT-2010-00005; 1/07/2010-30/06/2013) “Flexible injection of alternative carbon material into the blast furnace” Objectives: To improve deslagging and slag conditioning by monitoring and control of deslagging operations and by a dynamic online process models to monitor and control the slag properties. Results: EAF: Image analysis systems worked well providing images of each deslagging process; Process models at EAF plant calculated online; Slag composition and slag amount ; Amount of slag former additions. Desulphurisation station/BOF: Target values have been provided for permissible amount of remaining slag after deslagging, which was transferred into the BOF; To decide the impact of remaining slag on the steel quality and develop setpoint calculations for deslagging. To predict the sulphur amount in the produced steel.

- **PROTECT** (PROTECT, RFSR-CT-2010-00004; 01/07/2010-31/12/2013) "Processes and technologies for environmentally friendly recovery and treatment of scrap". Objectives: To develop an innovative method to promote synergetic use of low-value energy rich waste, combined with cleaning and preheating of zinc-containing steel scrap. Results: A pilot plant for the scrap preheating system and scrubber was constructed and the mechanical design of the plant was functioning well; Efficiencies up to 90% were achieved, based on the analysed zinc content in the scrubber solution; The scrap preheating concept could also be suitable for removal of mercury before charging to the melting furnaces; A model for de-zincing and reuse of scrap steel using pyrolysis of plastics, and one model for the same purpose using gasification of plastics were developed. The models were based on an LCA of the modelled process section.
- **REFFIPLANT** (REFFIPLANT, RFCS-CT-2012-00039; 01/07/2012-31/12/2015) "Efficient use of resources in steel plants through process integration" Objectives: To reduce BOF slag amount recovered in the internal quarry; to improve by-products management in order to reduce waste, environmental impact and costs; to achieve the "zero-waste" goal; to save costs, due to the reduction of limestone; to reduce landfill; to increase the reuse BF sludge, BOF sludge and sludge from the HRM after oil removal; to investigate the effects of BF flue dust injection into the BF; to recover secondary BOF dust via briquettes to BF, DeS or BOF; to optimize the mill scale reuse. Results: Optimization of internal (e.g. pellets) or external (e.g. fertilizer) reuse of BOF slag; distillation and pyrolysis for sludge/scale recovery and the Aspen Plus simulation results on oil removal efficiency, recovering pure oil, water and scale, and reducing sludge volume; washing process of oily mill scale and the Aspen Plus simulation; recycling wastes into the BF; recycling BOF fine sludge into the BF; recycling steel LS to the BF; recycling BF flue dust into the BF.
- **SLACON** (SLACON, RFSR-CT-2012-00006; 1/07/2012-31/12/2015) "Control of slag quality for utilisation in the construction industry" Objectives: To increase the utilisation of steelmaking slag in the construction industry by improving the quality of the EAF slag. Results: Investigation of different ways to improve EAF slag. In particular, addition of sand to decrease Ba, addition of sand or LF slag to decrease V, addition of aluminum oxide to decrease Cr, addition or storage/watering of LF to decrease free lime adjustment.
- **EIRES** (EIRES, RFCS-CT-2013-00030; 01/07/2013-31/12/2016) "Environmental impact evaluation and effective management of resources in the EAF steelmaking" Objectives: Reuse of LF slag in EAF as lime replacement; Charging rolling mill scale in EAF as scrap substitute. Results: Simulation showed that it possible to replace lime and dolime with slag, but only in the case of LF slag recovery (without recovery of EAF slag), due to the reduction of the non-metallic raw material of about 18% and due to an increase of only 2.5% of the required electric energy. Model simulation showed that the introduction of scale in the furnace did not change by-products and waste generation, as all the scale should have been reduced to iron. The increase of energy consumption was not negative, as globally the efficiency in material reuse was very high and balances the increase of energy consumption.
- **PSP-BOF** (PSP-BOF, RFCS-CT-2013-00037; 01/07/2013-31/12/2016) "Removal of Phosphorous from BOF Slag" Objectives: Adding knowledge and value by innovative methods and operational tests by: treatment of liquid slag with P- and Fe-containing residues to achieve successful separation and optimised recycling; investigation of two

different phosphorus separation methods: separation of liquid (partial) state and separation in solid state; investigations of potential applications of all obtained fractions. Results: Slag modification – slow cooling/partial solidification – mechanical separation could lead to utilize the total amount of all BOF slag fractions; Slag modification - slow cooling - standard pretreatment with metallic separation - fine grinding - magnetic separation, could not lead the utilization of the total amount of all BOF slag fractions; The pellets obtained by pilot scale in laboratory were used in the sinter pilot plant and BOF slag could be used into the sinter mix as pellets, without negative effect on productivity, quality and emissions; The possible use of BOF slag in agriculture needs to be proved by field tests, by the results achieved by soil column tests were encouraging.

- **GREENEAF2** (GREENEAF2, RFSP-CT-2014-00003; 1/07/2014 - 30/06/2016) "Biochar for a sustainable EAF steel production" Objectives: it was the logic continuation of the previous P22 (GREENEAF) project where the feasibility of the use of char from biomass as substitute of coal in EAF process was demonstrated. The new project aimed at solving all the previous issue so to make the biochar use a standard practice. Results: 1. The more appropriate materials to be used among the ones investigated were the residue from gasification, char from thermal pyrolysis and torrefied biomass; 2. Laboratory tests indicated a low tendency of biochar to promote slag foaming while biomass resulted to be more effective in promoting slag foaming but it caused temperature rise; 3. Long term trials in two different EAFs of Torrcoal biochar permitted to validate the char utilisation and to estimate the process parameters. No negative impact on steel or slag quality or in furnace operations were remarked. Furthermore, an energy saving around 6% has been obtained with a mix 50/50 coal/biomass used. The use of mechanically stable briquettes of biochar were beneficial to avoid material dispersion and ignition during the charging step; 4. Industrial trials in two different EAFs confirmed the difficulty to promote an adequate slag foaming by injecting biochar. The problem was due to both lower reactivity of biochar with FeO and to its lower density, this last aspect decreasing the efficiency of penetration of the injection into slag. Test with virgin biomass indicated a better tendency towards slag foaming but the trials were discontinued; 5. An LCA study calculated a potential CO_2 saving in using Torrcoal (biogenic carbon) for EAF charging of about 20%.
- **ALTERAMA** (ALTERAMA, RFCR-CT-2014-00006; 01/07/2014-31/12/2017): "Developing uses of alternative raw materials in cokemaking" Objectives: To develop the use of alternative materials not previously considered in cokemaking and delivering technological solutions to increase the potential of other materials for inclusion in coal blends while maintaining coke quality. Results: Investigations have shown that the selected surfactants can give similar or higher charge densities at lower addition levels to currently used industrial oils in coal blends.
- **RIMFOAM** (RIMFOAM, Recycling of industrial and municipal waste as slag foaming agent in EAF, RFSR-CT-2014-00008; 1/07/2014-30/06/2017) "Recycling of industrial and municipal waste as slag foaming agent in EAF" Objectives: To partly substitute carbon and oxygen with industrial and/or municipal waste (ASR, rubber tyres, plastics, biomass waste and byproducts, EAF dust and mill scale) for slag foaming purposes within the EAF. This project aimed to the exploration of a cost- and energy-effective alternative slag foaming agents maintaining or improving the slag foaming intensity, preserving the liquid steel quality and keeping emissions at a low level.

- **ACTISLAG** (ACTISLAG, RFCS-CT-2017- 749809; 1/07/2017- 31/12/2020) "New Activation Routes for Early Strength Development of Granulated Blast Furnace Slag" Objectives: To increase the value of the granulated blast furnace slag by improving short-term reactivity and to develop new products containing more than 80 wt.-% of granulated blast furnace slag with at least as good mechanical performance as CEM II class products are the main aims of this running project. The fundamental understanding of the relation between structure, reactivity and performance of industrial slags and the modification of the slag chemical and physical properties in liquid state were the two main issues.
- **FINES2EAF** (FINES2EAF, RFCS-CT-2017-754197; 01/07/2017-31/12/2020) "Cement-free brick production technology for the use of primary and secondary raw material fines in EAF steelmaking" Objectives: To increase the value of steelmaking residues, such as LF slag, through the internal recycling and their re-use as agglomerates in the form of cement-free bricks.
- **ECOSLAG** (ECOSLAG, RFCS-CT-2018-800762; 1/06/2018-30/11/2021) "Eco-friendly steelmaking slag solidification with energy recovery to produce a high quality slag product for a sustainable recycling" Objectives: To find technical solutions for heat recovery from EAF, LF and BOF slags while producing a high quality slag product for external or process internal utilization.
- **Slagreus** (Slagreus, RFCS-CT-2019-846260; 1/06/2019-30/11/2022) "Reuse of slags from integrated steelmaking" Objectives: To increase the internal and external recycling of the primary steelmaking slag. Investigation of an innovative process, consisting of a primary hot liquid and a secondary solid Fe-enrichment of BOF slag.
- **SLAGFERTILISER** (SLAGFERTILISER, RFCS-CT-2011-00037; 01/07/2011-30/06/2015) "Impact of long-term application of blast furnace and steel slags as liming materials on soil fertility, crop yields and plant health" Objectives: Investigation of fertilizer/liming properties of BOF and LF slag in agriculture and of the effects of Cr and V on soil and plant yield/health. Results: Soil investigation for Cr and V accumulation. After 3 years of fertilization it was difficult assessing metal accumulation due to the soil composition. Small increase of Cr and V in the soil. In some crops a small amount of Cr uptake with slag fertilization; in the tomato Cr was higher with BOF slag fertilisation than the control. With V the same is seen. No significantly consistent uptake of V in any particular crop with slag fertilisation.
- **E-CO-LadleBrick** (E-CO-LadleBrick, 2019 –2022) "Ecological and Economical waste management of the ladle refractory bricks by implementing circular economy criteria" Objectives: Achieving an innovative ecological and economical waste management focused on ladle bricks according to Circular Economy criteria based in environmental 4R model (Reduce, Reuse, Remanufacture and Recycle); Optimizing remaining final thickness for the bricks from ladle refractory by developing a 3D laser scanner technique with machine learning models and regression analysis. The developed approach can be applied in other steelworks; Optimizing the valorisation of the worn bricks from ladle refractory by finding suitable applications, including benefits and restrictions and implementing a data-based decision mechanism for best valorisation in either Reuse, Remanufacture or Recycle. The developed approach can be applied in other steelworks.
- **iSlag** (iSlag, G.A. 899164; 01/07/2020-31/12/2023)"Optimising slag reuse and recycling in electric steelmaking at optimum metallurgical performance through on-line

characterization devices and intelligent decision support system". In this ongoing project, the adoption of advanced ML-based data analytics and modelling (e.g. neural networks) is envisaged in order to process the data coming from novel sensing devices for on-line slag characterization and to predict the main slag features based on process and product data. Objectives: the main goal of iSlag project is to valorize the slag produced in the electrical steelmaking process by integrating innovative measurement devices with modelling and simulation systems, leading to sustainable practices and to reduce slag disposal costs, according to the "circular economy" concept. Meaningful outcomes: the evaluation of new ways for the slag recycling, by improved slag conditioning, will be carried out to implement a real IS. Innovative measurement tools will be integrated in modelling and simulation systems to assess compositions and amounts of liquid and solid EAF slag and LF slag. The information supplied by the different systems will provide information on slag properties to the decision support system, to be able to support the plant staff in choosing the optimal way for internal and external slags recycling.

- **BioReSteel** (BioReSteel, RFCS; 01/10/2023-31/03/2027). As one carbon neutral source, biocoal will play an important role to facilitate the transition of the European steel industry towards processes decarbonization. Objectives: the BioReSteel project focuses on exploring, developing and utilizing hydrochar (one type of biocoal), derived from various locally available biomass residues via the hydrothermal carbonization (HTC) process, in the EAF process. HTC unblocks to valorization of residual wet biomass feedstocks, which makes the hydrochar more economically competitive. Given the abundant biomass residues available in Europe, the hydrochar produced from only a few percent (< 2%) is sufficient to supply all operating EAF steel plants in Europe. By estimation, around 840,000 t fossil coal can be substituted by hydrochar at today's steel production level from EAF process, leading to a reduced fossil CO_2 emission of about 2.5 Mt per year. As additional sustainability aspects, phosphorus from residual biomass will be returned into circular economy saving resources of a critical raw material. In addition, heavy metals will be collected for decontamination of products and environment. The project will cover the whole value chain from biomass feedstocks, hydrochar production by an industrial HTC plant, up to its use in the EAF steelmaking of green steel. The project will consider all technical, economic and sustainability aspects. The BioReSteel concept will be proved by an experimental study by the means of laboratory and EAF testbed trials.
- **ZincVal** (ZincVal, RFCS; 01/10/2023-31/03/2027). The steel industry contributes greatly to the global economy but generates at the same time significant amounts of residues, of which most are valorised by internal recycling or external use, but, there are still substantial values in terms of carbon and iron units that cannot be recycled, due to too high zinc content in the sludge/dust (e.g. BF sludge, BOF dust and sludge, EAF dust with < 20% zinc) but too low for being sent to the zinc producers. Processing technologies applied outside the core processes are often not economically feasible. Objectives: ZincVal aims to develop technologies integrated with the steel production that enable recovery of iron, carbon and zinc from these and avoid landfilling. The approach of using six different technological routes at relatively low starting TRL and with synergies between some of the approaches represents a significant and credible due diligence approach to both increasing the valorisation of low zinc-content dust in current steelmaking practices and preparing for a significant increase in the availability of these

low zinc-content dusts in future steelmaking. Meaningful outcomes: by physical, chemical and mineralogical characterization of residues/intermediates, feasible methods are selected. Thermal treatment costs are reduced by recovery of a zinc-enriched fraction, in a high effective hydrocyclone innovatively designed in CFD modelling. Experiments, zinc enrich overflow are fed into OXYFINES burner, rotary kiln, or a rotary hearth furnace, if needed after agglomeration. EAF-dust and biochar briquette can be internally recycled. Zinc enriched in the dust can be recovered at zinc smelters or by selective leaching (zinc, lead). Zinc and lead separation by chlorination under thermal treatment are studied, and the removal of chlorine from the zinc product, e.g. by soda washing. The new process flow sheets will be technically, environmentally and economically evaluated. Results will be disseminated, communicated and exploited to identified target groups.

- **InSGeP** (InSGeP, RFCS; 01/07/2023-30/06/2027). Complying with the EU Green Deal, the RFCS objectives and Horizon Europe's Missions to move towards climate neutrality by 2050 with a zero-pollution ambition, it is essential to make sure that while introducing breakthrough technologies to produce green steel, the whole circular concept is kept in place, especially with respect to recycling of by-products, such as slag. Next generation iron and steelmaking process to decrease CO_2 by using direct reduced iron (DRI) with varying reduction degrees, hot briquetted iron (HBI), hydrogen plasma smelting reduction (HPSR) or by operating electrical smelters for low-grade ores will result in increase of EAF and other slags with different properties. This requires the understanding of the possibility to valorise future slags in the present value chain and define innovative applications to assure smooth transition process without disruption to the steel industry as well as other sectors (such as road construction or cement) who currently rely on slag as raw material for their processes. Objectives: to understand and move forward the transition of the steel industry, five steelworks, six RTOs and two suppliers will investigate slags resulting from next generation steelmaking in Europe in InSGeP project. The project will rely on the limited amount of currently produced slags from next generation steel production in Europe as well as on laboratory, pilot scale and industrial scale tests that will be performed based on the needs of the involved partners. The slags will be evaluated based on chemical, mineral, environmental and physical properties and will be treated with different cooling and granulation methods to produce physical characteristics needed for different applications and environmentally compatible products. Use of the slags in applications, such as road construction, cement/concrete, liming material or 3D printing will be tested. The InSGeP project will create guidelines for the use of slags from next generation steelmaking.
- **REINJECT** (REINJECT, RFCS; 01/03/2024-31/05/2028) project is directly related to RFCS Big Tickets Call objective 3 "Circular economy and sector coupling solution to meet the zero-waste goal for steel making". Objectives: specifically, SO1 and SO2 are directly related to sub-objective 3.3, which involves the use of secondary carbon carriers in metallurgical processes as a substitute for solid carbon fossil sources. SO3 is directly related to sub-objective 3.5, which involves the development or implementation of advanced technologies to reduce/reuse/recycle residues and by-products. Objectives SO5 and SO4 are related to the adaptation of the process and the demonstration of the injection of substitute materials in the steelmaking process, and therefore are related to sub-objectives 3.3 and 3.5. Ultimately, these two objectives aim to achieve the provisions set forth in Article 8 of the RFCS Research Programme ("New, sustainable and low-carbon steelmaking and finishing processes").

- **ADVANCE** (ADVANCE, RFCS; 01/09/2023-31/08/2025) The reduction of greenhouse gas emissions of steel industry became essential in the recent years with the major focus on the construction sector, the single largest source of its environmental footprint. The construction sector comprises the opportunity to establish steel-based technologies in a leading position for the decarbonisation of other relevant industries dependent on steel solutions. The activities supporting this goal can be divided into two categories (a) efficient and clean energy utilization in steelmaking and (b) taking advantage of excellent durability of steel products that enable their re-manufacturing and reuse without the need of energy intensive recycling. The project will focus on the latter category and utilize and further develop the outcomes of several successful background projects such as PROGRESS, SB STEEL and LVS3. Objectives: the project aims to contribute to greenhouse gas reduction and circular economy goals by addressing these challenges in both deconstruction and reuse of existing steel buildings, and in the design of new buildings, their construction and documentation to facilitate future reuse. Its scope includes reuse of constituent products, fabricated components, and reuse of component assemblies. The reused material may originate from primary structures, secondary structures and envelopes.

4.1.3 Other EU and not EU funded projects on Industrial Symbiosis deeply involving the Steel Sector

- **REZIN** (REZIN, FP5-G5RD-CT-2002-00652; 1/04/2002 – 31/03/2005) "Elimination of zinc ferrite" Objectives: To develop a method to transform the unleachable zinc ferrite in the dust into a leachable zinc oxide achieving two final products, zinc ferrite and zinc metal, and no waste.
- **REDILP** (REDILP, FP6-SME Ref.508714; 01/11/2004-30/04/2007) "Recycling of EAF Dust by an Integrated Leach-Grinding Process" Objectives: Development of a "cold" process to remove the heavy metals, as well as zinc lead oxide, from the dust and use the remaining iron containing material as ingoing material for the BF process. Results: Development of a hydrometallurgical process for recovering of Zn and Pb oxides of virgin quality. Development of applications for reusing iron oxide in blast furnaces. Development of an integrated closed loop alkaline leach-grinding process in order to improve the solubility of zinc and lead from EAF dusts. Cleaning of ammonium carbonate solution under pressure with fractionised separation of zinc- and lead carbonate.
- **RESLAG** (RESLAG, H2020 GA No. 642067; 01/09/2015 to 31/07/2019) "Turning waste from steel industry into valuable low cost feedstock for energy intensive industry" Objectives: To valorise slag from batteries recycling smelter by extracting high added value metals
- **ISAFA** (ISAFA, "Bando Ricerca e Innovazione In Campo Territoriale e Ambientale" No RFSR-CT-2011-00037) "Impiego della Scoria di Acciaieria come Fertilizzante in Agricoltura (ISAFA) (in English "Application of steelmaking slag as fertiliser in agriculture") Objectives: Investigation of the effects and the possible risks deriving from the use of Basic Oxygen Furnace (BOF) slag (due to some harmful trace element contents, such as Chromium and Vanadium) for amending purposes in two moderately alkaline soils.
- **INITIATE** (INITIATE, H2020-EU.2.1.5.; 01/11/ 2020–30/04/2025) "Innovative industrial transformation of the steel and chemical industries of Europe". The project aims at advancing the implementation of CE, IS and CCU through the re-use of residual steel

gases as a resource for the cross-sectorial, more efficient and less wasteful manufacture of urea, with a significant reduction of carbon footprint. Objective: The objective of the is to develop sustainable technologies to capture carbon-rich gas from the iron and steel industry and convert it into a valuable raw material for the chemical sector. The applied technology aims to combine the continuous production of N_2 + H_2 and CO_2 streams with the ammonia production as a precursor for urea, which is largely used as fertilizer. Results: Preliminary outcomes concern the definition of base and reference cases for steel, ammonia and urea production. Ammonia and urea plants have been simulated in Aspen Plus V11 while the power section of the steel plant in Aspen Plus V8.8. The primary energy consumption and the process carbon intensity of the base cases agree with the values found in literature. In the reference cases, the addition of the carbon capture section implied a reduction of the CO_2 emissions bur also an increase of PEC. This results in increase of cost of the final product (hot rolled coil, ammonia, or urea). For the stand-alone ammonia plants, the large-scale plants are more cost-effective than the small ones. This was true also when the ammonia plants are coupled with the urea plants.

- **Carbon4PUR** (Carbon4PUR, Horizon 2020-SPIRE-2017, 01/10/2017 – 31/03/2021) “Turning industrial waste gases (mixed CO/CO2 streams) into intermediates for polyurethane plastics for rigid foams/building insulation and coatings”. Carbon4PUR aims at transforming the CO_2/CO containing flue gas streams of the EII into higher value intermediates for market-oriented consumer products. A novel process based on direct chemical flue gas mixture conversion will be developed, resulting in the carbon footprint reduction and in high monetary savings. Objectives: The Carbon4PUR project aims at developing a new flexible technology to produce value-added chemicals, polyester polyols, of carbon from steel mill gas. In particular, the main objective are:
    - reducing carbon footprint of polyurethane intermediates compared to current polyurethane products manufactured from crude oil, due to the re-utilisation of anthropogenic CO and CO_2;
    - providing higher value novel polyols for the production of new, sustainable polyurethane applications (rigid foam and coatings), by matching market needs and requirements;
    - implementing a direct conversion of carbon from the steel mill gas mixture to building blocks for polyol intermediates production;
    - conditioning steel mill gas by avoiding traditional purification and conditioning methods, that are more expensive;
    - preparing Industrial Symbiosis between consortium in the Port Maritime de Fos (France);
    - demonstrating the economic and social feasibility of the new technology;
    - exploiting and transferring results to key stakeholders and to other EU industries.

      Results:
        - Developing knowledge and demonstrating an innovative technology to produce value added chemicals derived from steel mill gas streams.
        - Helping the EU process industry to reduce its dependency on imports of petrochemicals resources and to provide a secure supply of carbon feedstock.
        - Contributing to the reduction of the GHG emissions.

- Increasing the industrial competitiveness by adopting a novel production process of added-value chemicals.
- Contributing to the creation of new employment and job security in the EU industry.
- Contributing to Industrial Symbiosis.

- **REVaMP** (REVaMP, H2020/SPIRE, 01/01/2020–30/06/2023) "Retrofitting Equipment for Efficient Use of Variable Feedstock in Metal Making Processes". To ensure an efficient use of materials and energy in metal production plants will be retrofitted with dedicate sensors for scrap analysis and furnace operations; appropriate development and application of process control and decision support tools aim at improving the selection of the optimal material and energy feedstock. Furthermore, the development of model-based software tools aim at monitoring and controlling the melting process whose energy efficiency can be increased by scrap preheating systems. Three different use cases concern the electric and oxygen steelmaking, aluminum refining and lead recycling. Objectives: The project aims at:
  - Developing, adapting and applying novel retrofitting technologies to cope with the increasing variability and to ensure an efficient use of materials and energy through: 1) Novel sensors for characterisation of metal scrap on the chemical composition; 2) Metal scrap preheating system operated with waste derived fuel; 3) Software tools to model the operational input conditions; 4) Monitoring and control systems to optimise the processes for metal production at varying feedstocks.
  - Demonstrating within three different use cases from the metal making industry: Electric and oxygen steelmaking, Aluminum refining, Lead recycling.
  - Evaluating the retrofitting solutions in terms of economic and ecological effects, and cross-sectorial applicability to other process industries.

  Results: Expected results concern developing, adapting and applying novel retrofitting technologies to cope with the increasing feedstock viability, leading to:

  - Improved resource efficiency
  - Improved energy efficiency
  - Increased productivity
  - Improved and constant quality
  - Reduced carbon footprint
- **RecHycle** (RecHycle, Horizon.2.4-Digital, Industry and Space; 01/06/2022-31/05/2026) project will implement a gas hub to mix metallurgic gases produced on site with or without external green hydrogen sources. The product will be fed into a blast furnace and a future direct reduced iron furnace leading to sustainably produced green steel. The proposal represents a cost-efficient solution to decrease carbon emissions that will initiate a new symbiosis between the steel industry, the chemical industry and renewable energy sources. Objectives: RecHycle's goal is to implement a gas hub, capable of mixing metallurgic gases produced on site with or without external (green) hydrogen sources. This is to be fed ultimately into the Blast Furnace and a future DRI furnace to sustainably produce green steel. The project will demonstrate a cost-efficient solution to decrease carbon emissions by initiating a new IS between and within the steel industry, chemical industry and renewable energy sources (e.g. wind or solar to obtain green electricity or hydrogen). The project will contribute in the shift towards a

circular economy where waste products are valorised to the maximum of their potential. Meaningful outcomes: RecHycle will contribute to the transition towards a circular economy, through waste products valorisation to the maximum of their potential, and serve as a turning point towards the development of further development of synergies between companies within the North Sea Port industrial area, thus creating new opportunities for innovation and economic activities.

- **HURRICANE** (HURRICANE, Horizon.2.4-Digital, Industry and Space; 01/01/2024-31/12/2028) a sector-coupling circular hub centered around the ArcelorMittal Ghent site will be created, targeting efficient resource management together with the recovery and utilization of squandered industrial waste heat and water. This will lead to a reduction of energy, water and raw materials by at least 20%. Thanks to the ongoing projects taking place within and around the Ghent site, the site is already well connected to many other industries like waste suppliers, chemical producers (ethanol offtake & H_2 waste gas), renewable power producers, and wastewater treatment. It has become a multi-sectoral hub leading to efficient implementation of industrial symbiosis concepts. The Ghent site has a significant amount of recyclable energy, material and water that allows this symbiosis. These aspects are not only from the steel making processes, but also from other operations taking place in the mentioned "multi-sectoral" hub. This hub, can be further enhanced with the integration of waste heat with its ongoing initiatives. Objectives: the solution developed in the HURRICANE project aims at developing and demonstrating novel heat recovery (heat exchanger) and upgrading (heat pumps) solutions from selected operations and then coupling it with the internal and external off takers by means of a heat grid. With digital tools, aspects like broadening the district heating network, and adapting the heat demand profile of the buildings to better match the intermittent of the waste heat can be optimized. Finally, an integrated software tool for circular hubs that combines the different tools and data produced at the different operations will be developed and validated. Through two virtual demonstrations and a circular hubs blueprint the replication potential will be proven.
- **Carbon4Minerals** (Carbon4Minerals, Horizon.2.4-Digital, Industry and Space; 01/01/2023-31/12/2026) project will address the simultaneous use of CO_2 from industrial flue gases with current and future waste streams to release a vast stock of resources for innovative low carbon binders and construction materials. Objectives: the core concept of Carbon4Minerals addresses the simultaneous use of CO_2 from industrial flue gases with current and future waste streams to unlock a vast stock of resources for innovative low carbon binders and construction materials (80-135% lower CO_2-emissions than reference). A total of 8 industrial pilots will be built and operated across the process value chain from CO_2 capture to cement production and low carbon construction products. This cross-sectorial innovation has the potential to reduce European CO_2 emissions by 46 Mt/y, equal to 10% of the EU process industry emissions, while safeguarding the competitiveness of the European industry. Technical, environmental and economic feasibility will be validated by an integrated assessment, in combination with the development of a service life test package tailored to these new products. Co-learning modules are developed to support industrial implementation and market introduction.
- **RECONSTRUCT** (RECONSTRUCT, Horizon-CL6-2022; 01/06/2023-31/05/2027) project aims to counter this by replacing carbon-intensive materials with a blend of construction and demolition waste, sidestepping traditional Portland cement. Additionally, the project focuses on creating modular elements for easy disassembly, encouraging reuse and recycling. This circular approach integrates digital technologies, optimising

design, construction, and deconstruction processes. By digitising the construction cycle and regionalising supply chains, RECONSTRUCT will pioneer eco-conscious construction practices, mitigating the industry's environmental footprint. Objectives: RECONSTRUCT will (i) develop low-carbon alternatives to Ordinary Portland Cement (OPC), to be used in both renovations and new buildings, and incorporate Construction & Demolition Waste (CDW) and other waste as much as possible, (ii) manufacture construction components that use such materials and are designed for modularity and dismantling so they can either be reused or easily disassembled and recycled, (iii) embed deconstruction in building design and construct circular low-carbon buildings that produce near-zero CDW across their lifecycle. These objectives will become possible through (i) the digitization of construction materials, products and buildings, (ii) the extensive use of digital tools to support the design, construction and deconstruction phases of the circular building and (iii) the regionalization of the construction value chain through the creation of regional ecosystems of stakeholders covering all the aspects of circular construction. The RECONSTRUCT concept will be demonstrated by setting up to Territorial Circular Clusters, in Brussels and Barcelona, and using RECONSTRUCT's materials, components and innovative tools to design and construct two real-scale demonstrator buildings.

- **ZHYRON** (ZHYRON, Horizon.2.4-Digital, Industry and Space; 01/01/2024-31/12/2026). In the coming years, innovative DR shafts and EAFs will be installed in several steelmaking sites across Europe to follow the strategic decarbonization guidelines. The progression of these production processes will imply changes in the composition and management of generated by-products, especially for those containing Zn. Likewise, the large rate of fossil fuels/reductants needed in the current valorisation processes of these wastes make them very intensive in terms of CO_2 emissions, requiring the metallurgical industry to move to H_2 applications in its targeted pathway towards zero wastes goal. Objectives: to tackle complex challenges and to solve the recycling of key steelmaking by-products like EAF dust, BOF dust and sludges, DR sludge and pellet fines and mill scales (among others), ZHYRON will develop an innovative valorisation route for Fe-rich and Zn-containing by-products based on the combination of pyrometallurgical (using green H_2 as reductant) and hydrometallurgical stages The iron oxides units would be recovered as Direct Reduced Iron able to be consumed in EAF and the zinc would be recovered as zinc oxide concentrate to be used in zinc smelting sector, contributing thus to circular economy and industrial symbiosis approaches.

4.2 Chemical Sector

Some 20% of the annual Gross Domestic Product (GDP) of the European Union (EU) is due to the direct and indirect contributions of the chemical industry to EU Gross Value Added (GVA). More than half of EU chemicals are supplied to the industrial sector. The industry works along nearly all value chains and produces materials across industrial sectors ranging from pharmaceuticals and crop protection to the automotive sector, defence, construction, textiles and consumer goods, as shown in Figure 4.1.

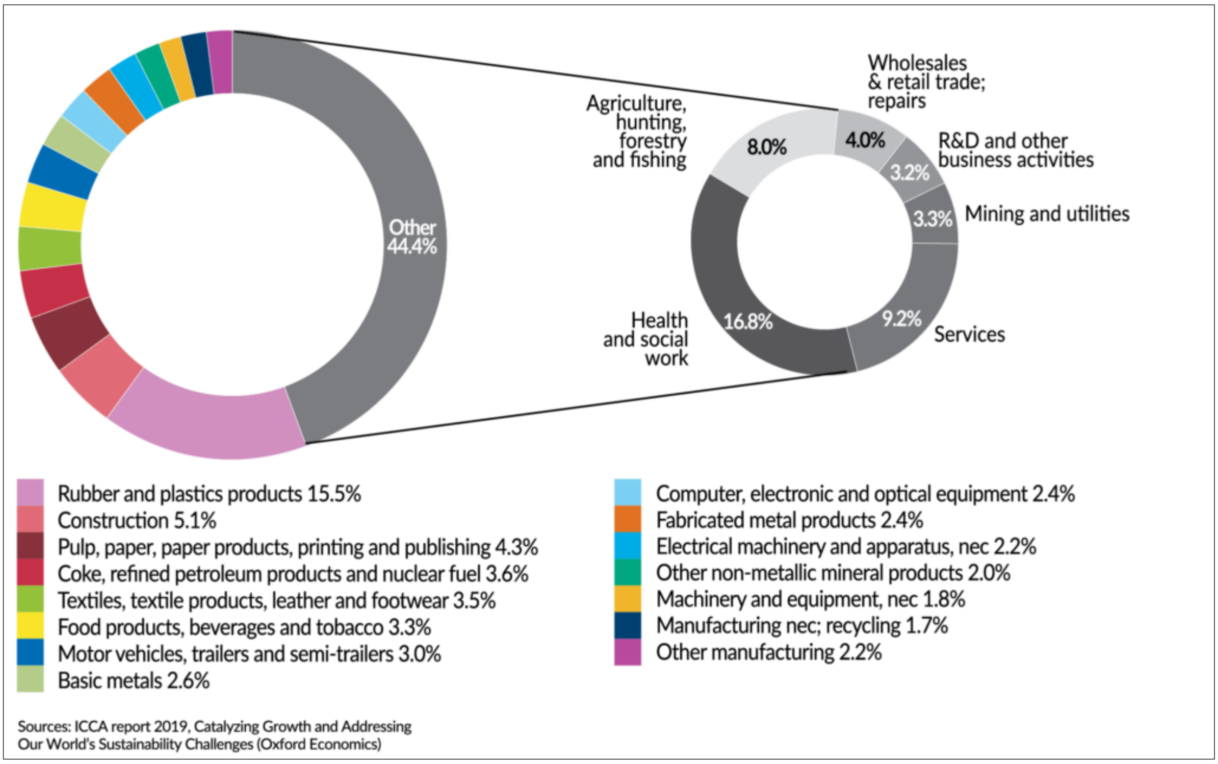

Figure 4.1: Customer sectors of the EU chemicals industry (2017). Source: ICCA report 2019, Catalysing Growth and Addressing Our World's Sustainability Challenges (Oxford Economics).

The European chemical industry plays a pivotal role in supporting Europe 2020: the EU's growth strategy for the next decade that aims to transform the EU into a smart, sustainable and inclusive economy. Sustainable chemistry is absolutely key to the future.

The European chemical industry is a solution provider for a competitive, low carbon and circular economy in Europe and beyond. It is a wealth generating sector of the economy, and a vital part of Europe's economic infrastructure.

The most significant figures of the European chemical industry are shown in Table 4.1.

Table 4.1: Most important figures of the EU chemical industry

Turnover	€565 billion
Number of companies	30,000
Capital spending	€22.8 billion
R&D investment	€10.0 billion
Direct employees	1,171,000

The Chemical industry plays an important role in promoting the development of global economy and human society. However, the negative effects caused by chemical production cannot be ignored, which often leads to serious resource consumption and environmental pollution. It is essential for chemical industry to achieve a sustainable development. IS is one of the key topics in the field of industrial ecology and CE, which has been identified as a creative path leading to sustainability. Based on an extensive search for literature on linking IS with the chemical industry, three aspects are identified:

(1) The chemical industry can achieve both economic and environmental benefits by implementing IS

(2) establishing eco-industrial parks is essential for the chemical industry to implement and improve IS

(3) there is a close relationship between IS and safety issues of the chemical industry

(4) there is also a close relationship between IS and closing circularity loops by upcycling. Upcycling refers both to solid waste and to fluids (incl. exhaust gases). Both sources can deliver – after chemical/catalytic/biotechnological recycling process alternative raw materials for the process industry and thus help to reduce the consumption of the limited crude oil reserves, at the same time reducing the environmental impact.

The chemical industry is one of the largest manufacturing sectors in Europe; it plays a key role in providing innovative materials and technological solutions to support European industry competitiveness.

This sector is currently undergoing rapid structural change as it faces major challenges, including increased competition from other countries and rising costs. The chemicals industry represents a fundamental pillar for the whole EU economy as shown by the following list:

1) represents around 7.5% of EU industry by turnover
2) Europe is the second largest chemicals producer in the world and has sales amounting to €565 billion (2018), which is about 17% of global chemicals sales
3) provides 1.2 million direct highly-skilled jobs (2015)
4) creates an estimated 3.6 million indirect jobs and supports around 19 million jobs across all value supply chains
5) has a labour productivity 77% higher than the manufacturing average
6) generates a trade surplus of €45 billion (2018).

The EU chemical sector is very innovative and new forms of industrial cooperation are emerging between chemicals and other industries, moreover chemical industry involves several material and energy flows and it is suitable for the development of industrial symbiosis and circular economy. The chemicals industry is also a strong driver of resource and energy efficiency and a potential solution provider for targets of the Green Deal.

4.2.1 Project on Industrial Symbiosis in the Chemical sector

E4WATER (E4WATER, FP7; 01/05/2012-30/04/2016) "Economically and Ecologically Efficient Water Management in the European Chemical Industry". Chemical Industry provides the highest potential for increasing eco-efficiency in industrial water management. E4Water addresses crucial process industry needs, to overcome bottle necks and barriers for an integrated and energy efficient water management. The main objective is to develop, test and validate new integrated approaches, methodologies and process technologies for a more efficient and sustainable management of water in chemical industry with cross-fertilization possibilities to other industrial sectors. E4water unites in its consortium large chemical industries, leading European water sector companies and innovative RTD centers and universities, active in the area of water management and also involved in WssTP and SusChem and collaborating with water authorities. Objectives: developing, implementing and validating new integrated approaches, methodologies and process technologies for a more efficient and sustainable management of water in Chemical Industry achieving solutions that are eco-efficient, cost-effective and industrially relevant. Meaningful outcomes:

- utilisation of alternative water sources
- treatment of organic and inorganic wastewater streams and concentrates
- recovery of valuables and energy from wastewater
- linking process water and cooling water networks
- combining different scales in water management (process – plant – site – local - regional)
- introducing tools to optimize water management
- Life Cycle Assessment of selected measures
- considering regulatory framework aspects.

4.2.2 State of the art of the industrial symbiosis in consumable goods companies

The consumer goods industry as a whole is of high relevance for the European economy.

Multinationals like Nestlé, Procter & Gamble, and Unilever shape the public perception of the consumer goods industry (Petersen, 2017).

The European consumer goods industry features some global players as well (e.g. Henkel and Maxingvest). Despite containing these internationally recognized companies with multiple billions of annual turnover, the European National consumer goods industry as a whole is characterized by a majority of small and medium-sized enterprises (SME) Many studies calculate the average consumer goods company to achieve an annual turnover of EUR 28 million and to employ 110 people (2010, p. 16). Thus, most companies fall into the category of SME as defined by the European Commission. However, large differences between the individual branches exist. The much higher number of textile or publishing companies turn over less than EUR 20 million per year and employ less than 100 people on average (Kern, 2010)

In the last years, these companies employed next to one million people and produced and sold durable and non-durable goods worth nearly EUR 300 billion. This combined turnover comprises about a fifth of the overall manufacturing industries. Also, the demand for consumer goods to a large degree determines the demand for intermediate and Multinational consumer goods companies are developing circular business models and investment goods (Kern, 2010) This holds true due to the large supply networks unfolding upstream from the consumer goods companies ((Schilling, 2012). Considering, for example, the production of plastics products like toys, intermediate goods like synthetic granules are needed as inputs and investment goods like injection molding machines are necessary to process the intermediate goods. The growth or decline of people's propensity to consume therefore immediately reflects on other manufacturing industries and immediately reflects on the national and European strategies.

Multinational consumer goods companies are developing circular business models and industrial symbiosis in their production approach and economic development strategies. Some operating methods have been identified as incentive actions for these strategies. They are:

- Industrial symbiosis.

- Closed loop recycling: the core of CE for chemistry is chemical recycling technology and the use of recycled substances for precursors of products.
- Downcycling: transformation of materials from one or more used products into a new lower quality product. This represents a limitation to be overcome by the development of new technologies.
- Recycling: transformation of materials from one or more used products into a new product, produced by a third company.
- Collection services: provision of a service for the collection of old or used products.
- Product service system: offers that focus on offering a solution rather than just a product. This leads to a marketable set of common products and services that can meet the needs of a user together.
- Modularity: a design that divides a product into smaller parts , built by different industries, that can therefore be created, used and replaced independently (and not as a whole)
- Lock-in: an offer that encourages consumers to continue using a specific product or service derived from one or a group of companies, on a regular basis.
- Local circuit: as production processes are reintegrated in the countries where the company has its main markets, the local production circuit approaches and benefits the grouping of industries
- Customization: The company creates data management opportunities that allow product customization. These data can also be shared by related or complementary companies for more efficient management of the offer.

From Nespresso and M&S Schwopping to the Nike Reuse-A-Shoe initiative and Ecover's Glocal project (Hoeven, 2014), for each business case, there are more details on the potential growth opportunities of the market, the potential for general application to the type of industry for production of consumer goods and for the appropriate scalability. In fact, each of these examples can and must be an inspiration for all production companies, for the creation of products, which from their design must be designed to be targeted, reusable, with little impact, useful for the same or for symbiotic companies with the same.

Customised Production example-Geneu- Unilever (Unilever, 2020)

An example that seems far from the application of industrial symbiosis for energy companies is that related to Geneu . The action taken by Unilever, on the other hand, is an example that hopes to really incentivize and inspire all production industries to think differently about product life cycles and to experiment with targeted designs and material choices. All this in order to provide only the suitable good, avoiding its waste, encouraging its intelligent use and sharing data for a more efficient offer.

Ecover's Glocal project (Hoeven, 2014), om Domen, manager long-term innovation at Ecover, highlights the thoroughness that characterises the project. On Mallorca, the University of the Baleares cooperates in the project; it made an inventory of all possible feedstock streams on the island. And so does the University of Barcelona, that is knowledgeable on the processing of olive and orange waste streams. For the project, the potential for biomass production has been estimated from remote sensing images. Ecover works together with local companies in a consortium, that has applied for a grant for the project under the EU innovation program Horizon 2020.

4.3 Refining Sector

4.3.1 State of the art of the industrial symbiosis in the refining industry

In recent years, the increased effort in oil and gas exploration and production, as well as cost reductions achieved in these activities, has resulted in the stability of the recognized reserves worldwide.

In 2019, the world's oil refinery capacity reached over 101 million barrels per day. Overall, global refinery capacity has more than doubled in the past fifty years. The world's largest refining region is Asia (25 % of the total existing), followed by North America and Europe (around 20 % each one). The top refining countries in the world are the US, followed by China, Russia and Japan (Statista, 2020).

The European market is characterized by a growing demand for petrochemicals, kerosene and diesel, and a declining demand for gasoline, light heating oil and heavy fuel oil. There is ongoing competition because of the increasing capacity in the Middle East and Asia.

EU refineries are still not producing the mix demanded by EU consumers due to their technical design. They cannot satisfy the existing demand for diesel, and they continue to produce gasoline in excess.

Refineries are classified according to the number of processes available for transforming crude into petroleum products.

Simple refineries are designed to distil crude oil into a limited range and yield and products. They are referred to as topping or hydroskimming plants. Topping is the most basic distillation process. Hydroskimming involves distillation in the presence of hydrogen.

Complex refineries involve a combination of interrelated processes to produce a broader range of refined products. They commonly utilize thermal and catalytic cracking that enables deeper conversion of the crude oil feedstock into higher yields of more valuable and marketable products.

Some examples of symbiotic activities involving the refinery sector are provided in the following list:

- Kalundborg symbiosis (Chopra, 2014) represents a model of environmental sustainability. Four industrial facilities—a power plant, an oil refinery, a plaster-board manufacturing plant, and a biotechnology production facility—and the local municipality participate in the Kalundborg symbiosis. In this industrial park the four industrial facilities exchange materials and energy flows in symbiotic way in order to favor the reductions in resource consumption, emissions, and waste The most significant achievements of the industrial symbiosis cooperation at Kalundborg are:
  1. significant reductions in energy consumption and coal, oil, and water use;
  2. reduction of the environmental impacts through reductions in SO2 and CO2 emissions and improved quality of effluent water; and
  3. Conversion into raw materials if the traditional waste products such as fly ash, sulphur, biological sludge, and gypsum.
- The Taranto industrial district (Notarnicola, 2016) represents an industrial area with various energy intensive industries such as: steelworks, oil refinery, cement industry and power stations where the implementation of industrial symbiosis can bring several benefits. The results of research project, funded by the Caripuglia Foundation, for a study of industrial symbiosis in the Taranto industrial district. The final results of this

study show thant the full implementation of IS in an area like that of Taranto will be feasible only if the Industrial Ecology paradigm is adopted at a system level with, if necessary, a radical restructuring of the industrial system to render it sustainable in economic, environmental and social terms. With this in view, the potential exchanges identified in this work, once definitely verified, together with the full involvement and coordination of the firms of the district will represent a tangible implementation of IS relations that could effectively make the industrial system of the Taranto province more environmentally sustainable and competitive.

- Grangemouth Development Group (GDG) (Harris, 2004). GDG is an organization formed in 1992 and consists of the major companies at Grangemouth, the Local Enterprise Council, Forth Ports, and Falkirk District Council. Meetings held every three to six months allow members to present and discuss ideas with the primary aim of improving the competitiveness of the local chemical industry and creating further jobs. The projects reveal a 'snowball effect' that drives the company culture towards further cooperation and outsourcing, at a time of increasing competitiveness increasing the efficiency of chemical use and where possible recover the chemical at the end of its lifecycle. BP Castrol, for instance, provides total fluid management services to UK Airbus' maintenance department.
- A network of interfirm exchanges in Guayama, Puerto Rico provides another example of industrial symbiosis (Chertow M. L., 2005). Guayama hosts many of the same industries as Kalundborg: a fossil fuel power generation plant, pharmaceutical plants, an oil refinery, and various light manufacturers. Current exchanges in Guayama include the new AES coalfired power plant using reclaimed water from a public wastewater treatment plant (WWTP) for cooling, and providing steam to the oil refinery. Additional steam and wastewater exchanges are under negotiation between neighboring pharmaceutical plants, the refinery, and the power plant. Beneficial reuse of the coal ash has begun as a means of stabilizing some liquid wastes. There is clear evidence of substantial public environmental benefit: for example, a 99.5% reduction in SO2 emissions due to steam generation for Chevron Phillips is achieved, and AES avoids extracting 4 million gallons per day of scarce freshwater through the use of treated effluent from the wastewater treatment plant.
- The Campbell Industrial Park (M. Chertow, 2010) is also the largest industrial park in the State of Hawaii, a core group of these companies have self-organized to form what we are calling the Campbell Industrial Symbiosis, a resource or by-product exchange network, anchored by the only coal-fired plant on Oahu, owned by AES Corporation, which generates approximately 180 MW. There are coal plant are the oil-fired Kalaeloa cogeneration plant (210 MW) and two large oil refineries. These oil refineries operate small (~9 MW) cogeneration plants and steam boilers and other industries. The Campbell Industrial Symbiosis group are organized to highlight the major materials being exchanged: various grades of water and steam; unconventional fuels such as granular activated carbon (GAC), waste oil, and shredded tires; ash; and sewage sludge (biosolids). The application of LCA to the Campbell Industrial Symbiosis shows that the environmental benefits are positive for all impact categories and all exchanges, save for one type of alternate fuel. The absolute values of these benefits are also important in showing how industrial symbiosis within a single industrial cluster can, on its own, represent significant progress toward a statewide GHG policy goal.

- The Ulsan/Mipo Onsan industrial complex (Won, 2006) is the largest industrial area of petrochemicals, automobiles, shipbuilding and nonferrous metals in Korea. Over the past decade, a few companies in Ulsan have been interested in trading their excess materials from the production line for economic purpose, but the increasing numbers of companies are participating to the industrial symbiosis (IS). By the recovery of previously discarded waste or by-products and recycling of wasted heat and water, Ulsan Eco-Industrial Park project team is taking the head for designing and implementing the industrial symbiosis by which the companies can sustain economically and environmentally. The current evolution of industry collaboration in Ulsan industrial parks provides testimony for the contribution that IS can make to sustainable development at the regional scale.

Industrial sludge is considered a waste and its main final destiny is landfill disposal. The changes in the surrounding conditions, the ever-increasing quantities produced as a result of the growing number of industrial purification plants and the more restrictive regulations on landfill disposal, force to consider with ever greater attention alternative methods to disposal of these wastes. In this context, this ENI R&M project was developed: "Pilot Plant for the Gasification of Oily Sludge and the Inertification of the Ash resulting from the Process". It aimed at setting up a plant and a self-sustaining process to treat the refinery sludges, producing a minimum of inert final residues (from the perspective of the wider ENI R&M “zero-waste” project) without supporting of external energy, as can be found in 3 patents (Process and apparatus for the thermal treatment of refinery sludge. us2012184797 (a1): us8969647 (b2); 03/03/2015, s.d.) (An energy recovery apparatus suitable for heat treatment of fluids or solids ;us2012184797 (a1);19/07/2012; us8969647 (b2) 03/03/2015, s.d.) (Waste sludge incinerator using pyrolysis and gasification, and relative process ; us2016245508 (a1), s.d.).

The plant is a pilot-sized demonstrator (50 kg / h), but able to prove the feasibility of the technology. It is composed of two main reactors (a gasifier and a plasma inertizer), with a wide flexibility that it can also treat other organic and inorganic waste produced by ENIi's plants.

The tests carry out on the plant have permitted to verify:

1. the feasibility of the technology, in terms of continuity of the process from sludge charging to ash discharging;
2. the real percentage reduction in volume of the input material equal to 74%;
3. The capability of the process to self-sustaining through the combustion of the syngas.

4.4 Non-ferrous metals Sector

4.4.1 State of the art of the industrial symbiosis in the non-ferrous metals sector

The European non-ferrous metals industry made significant steps toward sustainability. In the last 30 years a high level of electrification and recycling have been implemented. The sector is still strongly involved in such direction to contribute to the objectives of the EU 2050 climate-neutral strategy.

The present status of the non-ferrous metal industry and the vision for next decades are synthesized in the Report: “Metals for a climate neutral Europe – a 2050 Blueprint”, prepared by the Institute for European Studies (IES) for Eurometaux, the European non-ferrous metals association (IES, 2018)

This report considers the base metals, silicon, ferro-alloys, precious metals, specialty metals and rare earth elements.

The following classification is adopted.

- Base Metals: Aluminium, copper, lead, nickel, tin, zinc (+ silicon & ferro-alloys)
- Precious metals: Gold, Silver, Platinum, Paladium, Ruthenium, Osmium, Iridium, Rhodium
- Specialty metals: Cobalt, Germanium, Gallium, Indium, Selenium, Antimony, Magnesium, Molybdenum, Cadmium, Beryllium, Bismuth, Chromium, Niobium, Vanadium, Hafnium, Lithium, Manganese, Rhenium, Tantalum, Tellurium, Titanium, Tungsten
- Rare earth elements: Neodymium, Dysprosium, Scandium, Cerium, Erbium, Europium, Gadolinium, Holmium, Lutetium, Ytterbium, Thulium, Lanthanum, Praseodymium, Samarium, Terbium and Yttrium

Non-ferrous metals have a very great importance in our society. They are essential in infrastructure like buildings, transport, electronics; in strategic sectors like defense and telecommunications; they are present in almost every other economic sector, such as food, jewellery and so on.
Non-ferrous metals are particularly indispensable and irreplaceable in the production of low-carbon technologies. Consequently, the transition to a climate neutral economy can be expected to be metals intensive.
The non-ferrous metals industry in Europe is worth 120 billion Eur, employing around 500000 persons directly and more than 2 million people indirectly. The sector consists of 931 facilities, including mining (54 facilities), primary and secondary production of metals (464) and further transformation (413). Metals production is present in most EU member states with a large presence in Italy (179 facilities), Germany (147 facilities), Spain (116 facilities), France (82 facilities), UK (53 facilities), and Poland (51 facilities) (IES, 2018).
The total European production of non-ferrous metals is around 47 Mt [https://eurometaux.eu/about-our-industry/key-industry-data/].

Production, resources and import/export balance

Basically, regardless the different technologies, specific for each metal, all the metals are produced in two ways: The primary production process involves the conversion of ore to metal; the secondary production is the recycling of metal scrap. (IES, 2018) report the following data, summarizing the European situation in the non-ferrous metals industry.

The EU primary production of non-ferrous base metals in 2016 was 13 Mt of 128 Mt of global production (10%). The primary production was 6.5 Mt of 101 Mt (6%) and secondary production was 6.5 Mt out of 27 Mt (24%).

Aluminium is the most used non-ferrous metal by volume and the second most widely used metal after iron both in the EU and globally. In 2016 primary production of aluminium was 2.2 Mt (4% of the global production) in 2016; secondary aluminium was 3Mt, (30% of the global production)

Copper is the second largest base metal sector in the EU. In 2016 the production of primary copper was 2.3 Mt (13% of the global production); the secondary copper production was 1.7 Mt (23% of the global production).

In the last years (data from 2015 to 2018) the production of primary and secondary other base metals was the following (absolute value and percentage of the global production).

Zinc: 1.7 Mt (13%) – 0.3Mt (19%);

Lead: 0.4 Mt (9%) – 1.3Mt (18%);

Nickel: 0.2 Mt (10%) – 0.2 Mt (29%).

Figure 4.2 shows the EU Primary Production as a % of World Production

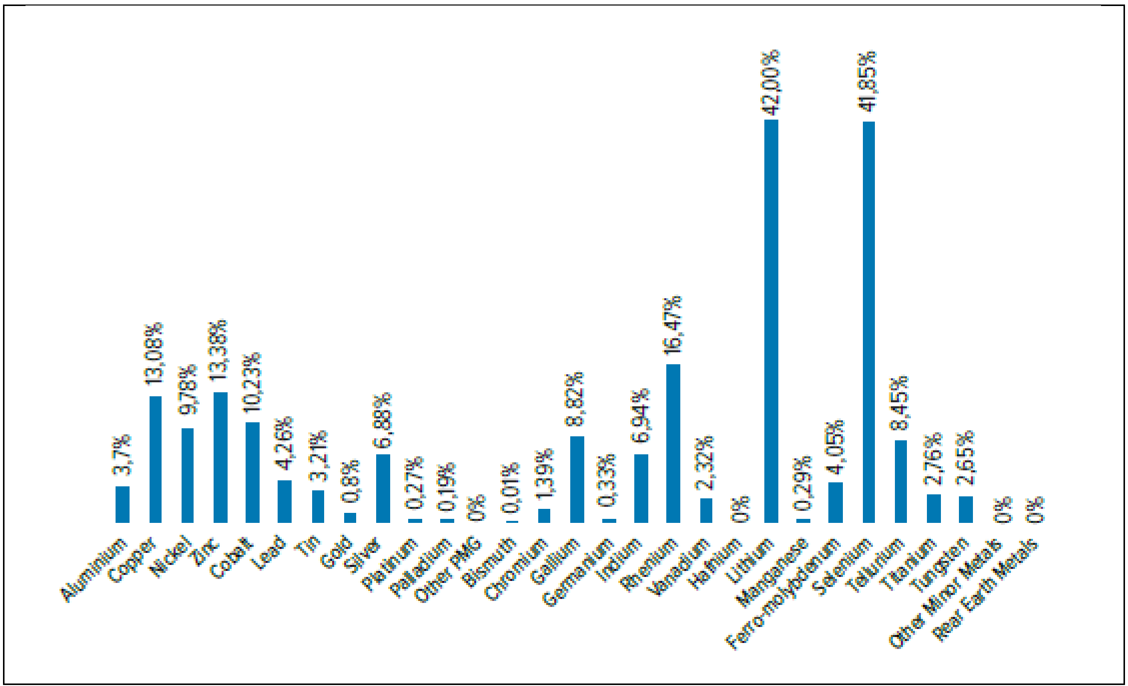

Figure 4.2: EU primary production of non-ferrous metals as percentage of the global production [IES, 2018]

The extractive industry (mining) of non-ferrous metals sector in Europe is a small sector, because of the scarce ore reserves present in Europe. EU mining has a small share in global ores production: 0.6% for bauxite (aluminium), 4.1% for copper ores, 3.0% for nickel ores, 5.4% for zinc ores and 1.0% for cobalt and 9.7% for lead ores.

There is no extraction of antimony, beryllium, borates, magnesium, molybdenum, niobium, phosphorus, tantalum, titanium, vanadium and rare earths. The only raw materials for which an EU Member State is the main global producer is hafnium (France).

Therefore Europe relies heavily on metal ores and concentrates imports from other continents – almost 80% of its needs.

The EU has a large import dependency as concerns base metal ores - 84% for aluminium (bauxite), 82% for copper, 78% for tin, 71% for zinc (concentrate), 59% for copper, 48% for cobalt.

The EU has 100% import reliance for the vast majority of non-ferrous metal ores. In particular the EU is 100% reliant on rare earth imports, where China is the top producer.

100% import reliance for several critical raw materials means that Europe is entirely dependent on third countries.

The EU has a negative trade balance in imports and exports of non-ferrous metals.

Imports into EU increased in the past two decades from 9.9 Mt in 2000 to 12.5 Mt in 2017. Exports also increased over the same period, from 3.8 Mt in 2000 to 6.2 Mt in 2017. The net negative balance is around 6Mt/y. The same situation happens for base metal ores, with a total negative balance of around 20 Mt in 2017. It is worth to mention that there is also an important trade of waste and scrap, especially concerning copper and aluminium. The EU exports 2.1 Mt waste and scrap, against 0.9 Mt import of the same.

Importance of non-ferrous metals for industry and civil life

Non-ferrous metals are of strategic importance for Europe.

The following Figures 4.3-4.6 show the main application sectors of the various categories of non-ferrous metals (IES, 2018). The figures evidence the large number of industrial sectors, ranging from essential to high technology and sensitive sectors, where non-ferrous metals are indispensable.

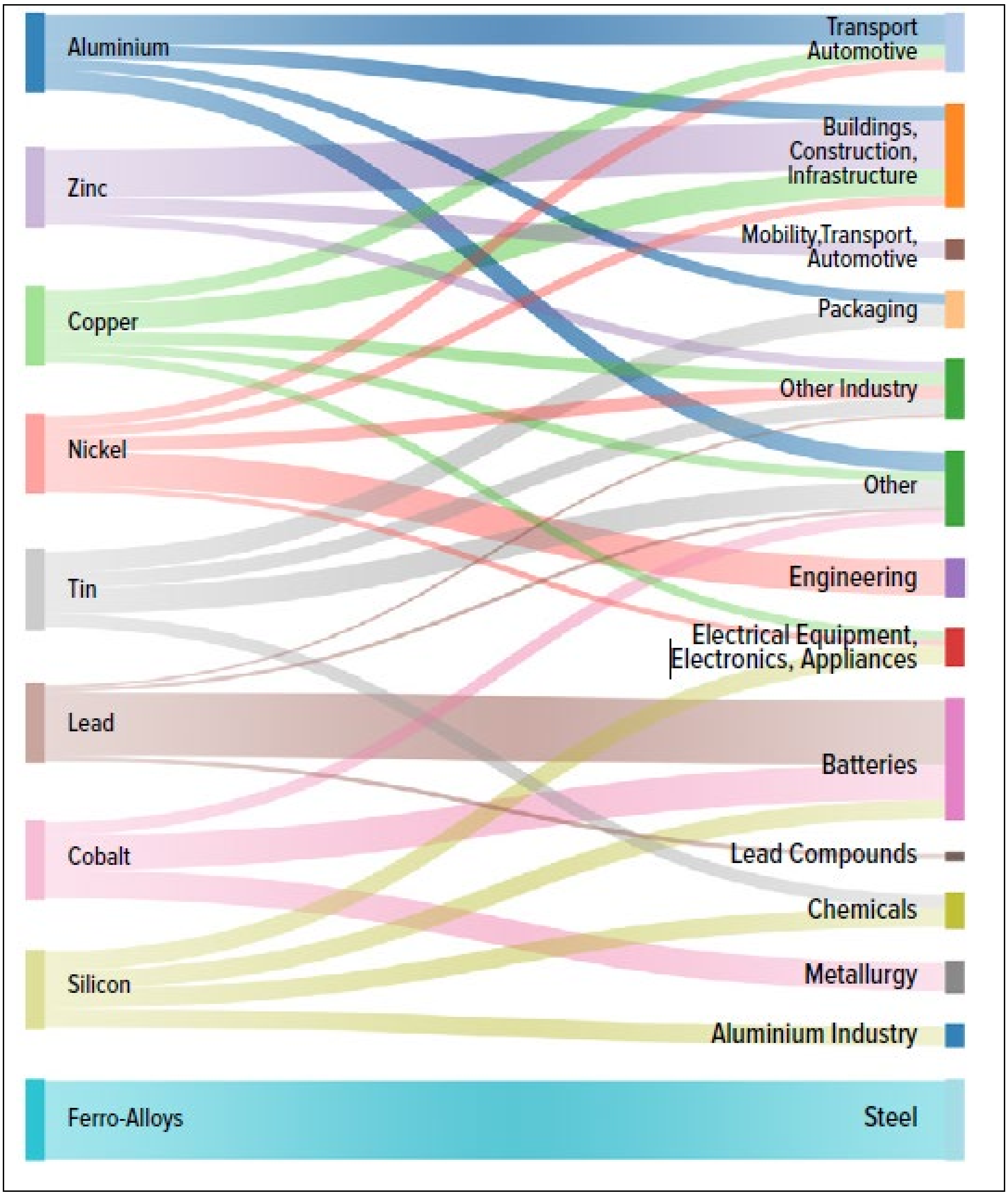

Figure 4.3: End sectors of base non-ferrous metals [IES, 2018]

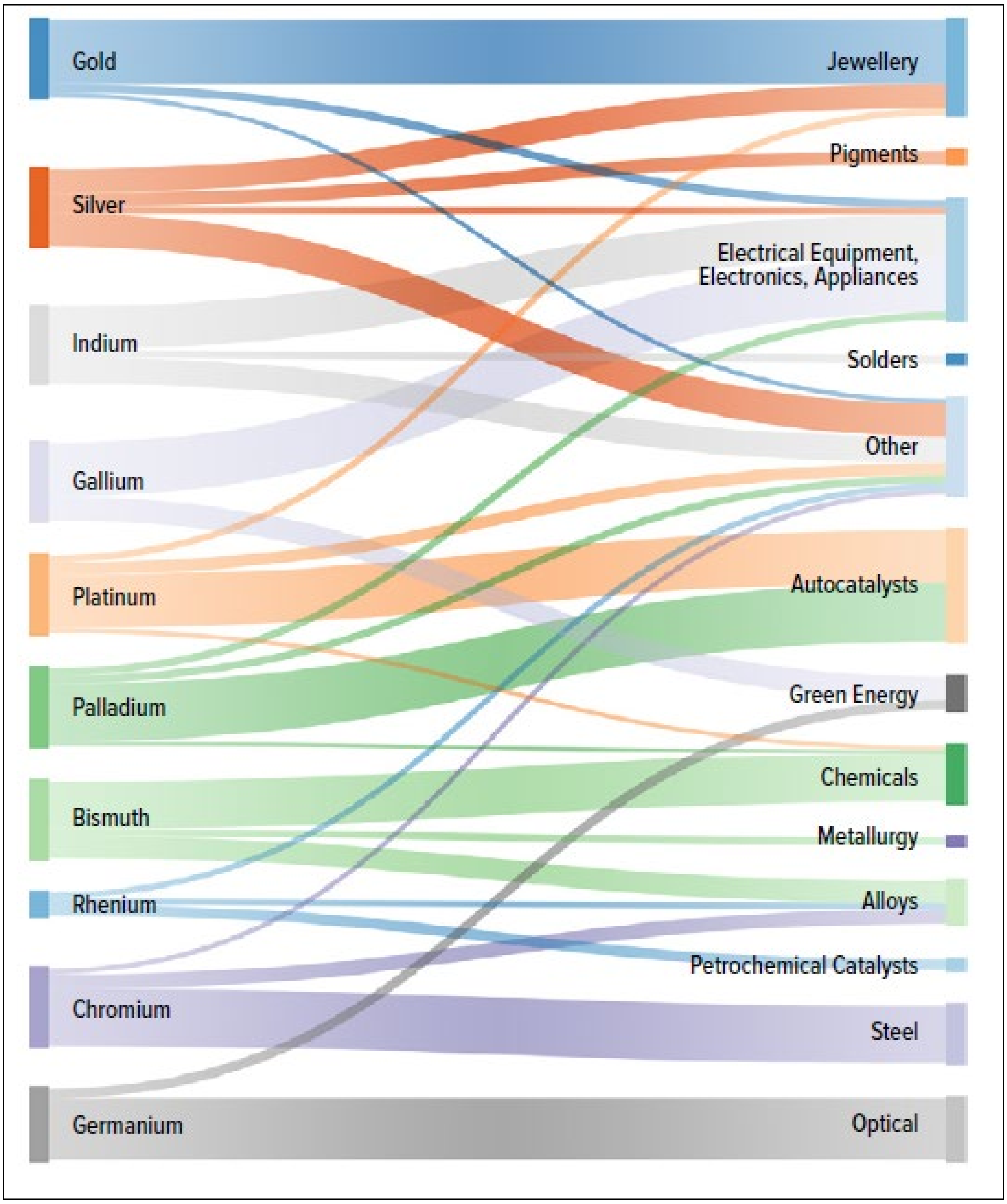

Figure 4.4: End sectors of base precious metals [IES, 2018]

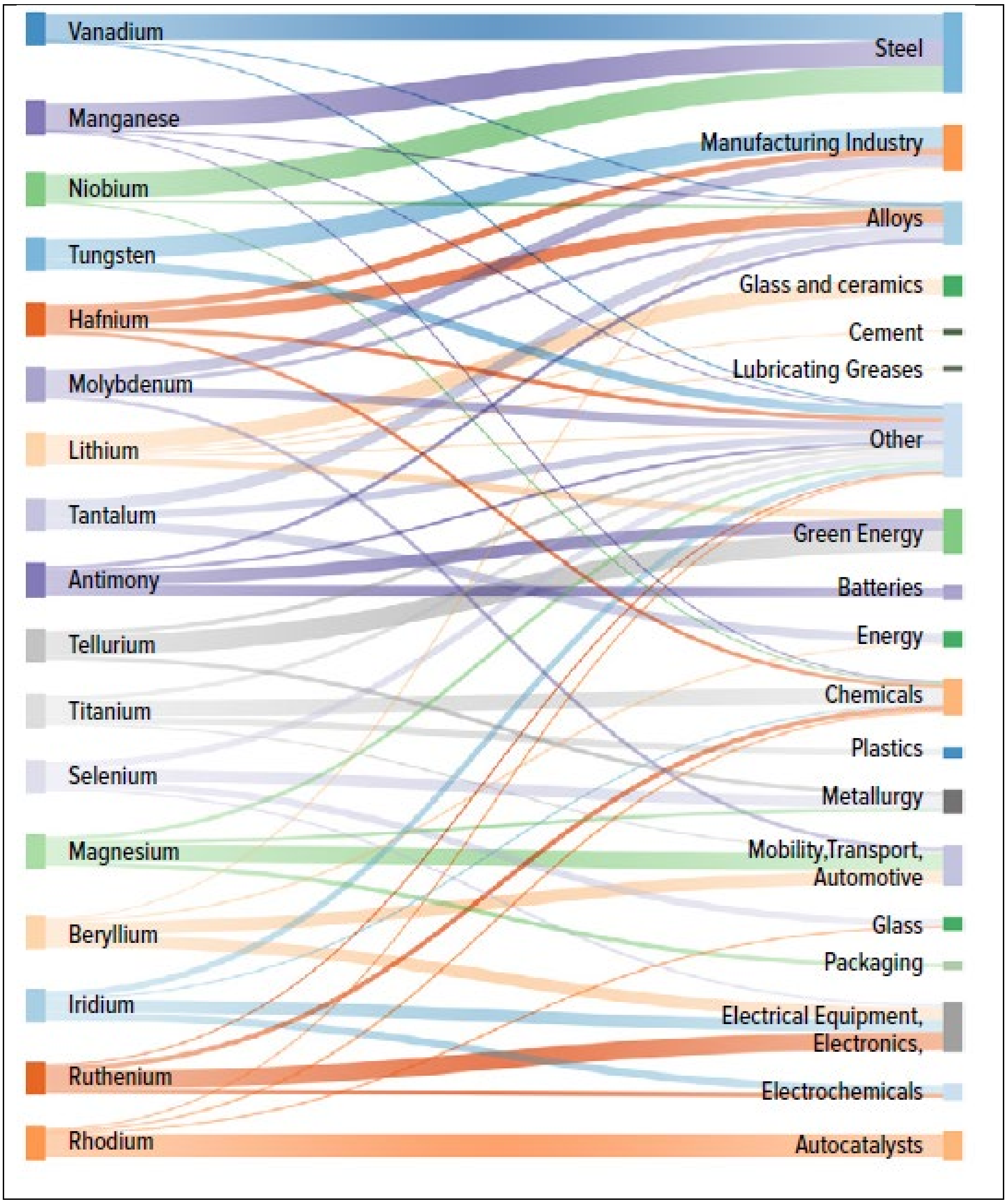

Figure 4.5: End sectors of base specialty metals [IES, 2018]

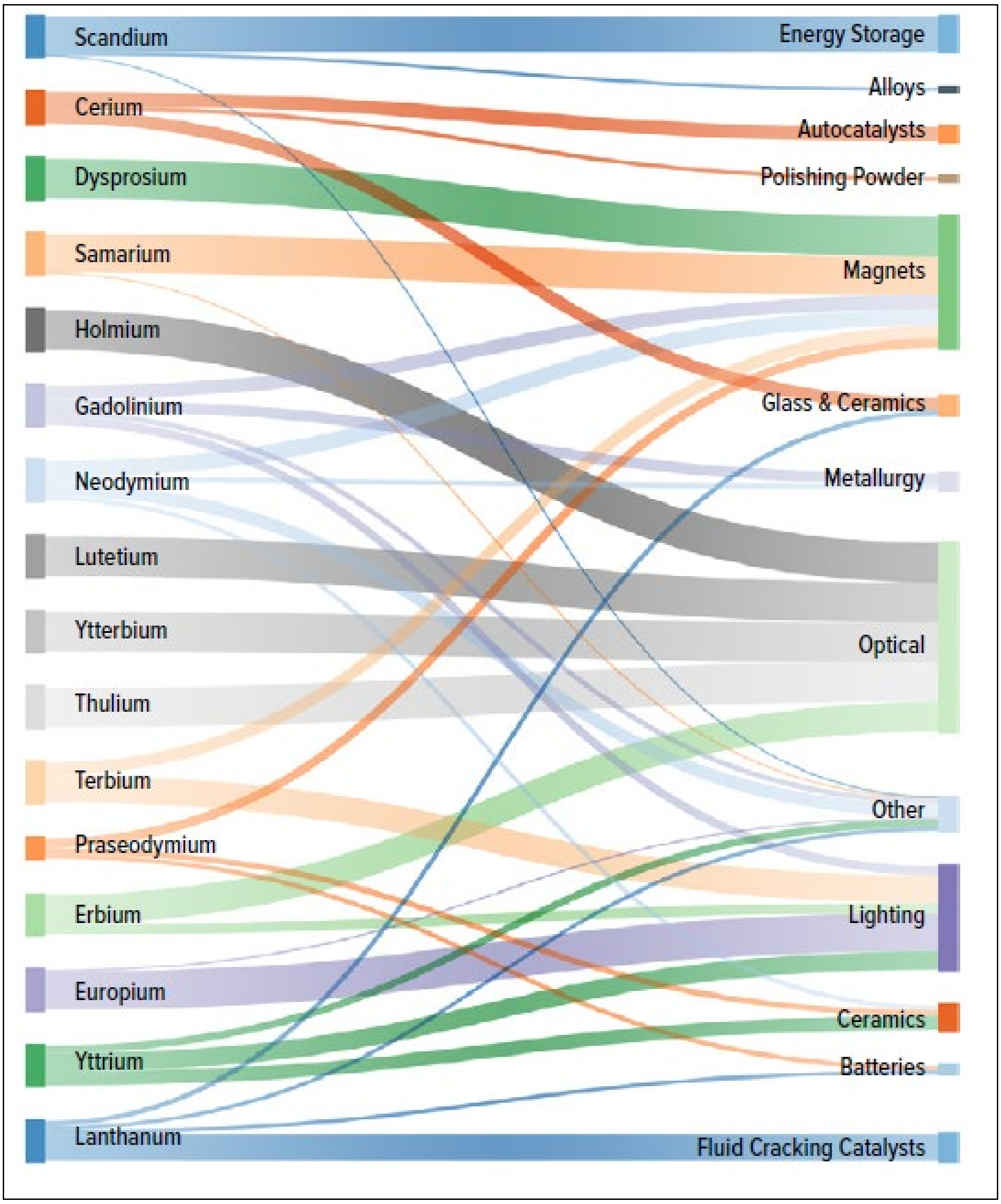

Figure 4.6: End sectors of base rare earth metals [IES, 2018]

Importance of non-ferrous metals for decarbonization

The transition to a carbon neutral Europe will be achievable only with sufficient amounts of non-ferrous metals.

Non-ferrous metals are practically used and not replaceable in all the technological solutions for decarbonization. Examples are battery and fuel cells for electrical based transport systems; solar photovoltaic panels panel and wind turbines for producing renewable energy; battery storage and smart grids, 100% recyclable packaging, and so on.

The low-carbon transition will require much more non-ferrous metals. The Organisation for Economic Cooperation and Development (OECD) estimates that the total consumption of will increase from 7 Gt to 19 Gt per year by 2060 (OECD, 2018).

Many studies forecast a significantly higher quantities consumption of aluminium, cobalt, copper, lead, zinc and nickel, and of course lithium, because of the diffusion of the decarbonization technologies.

Attitude to the non-ferrous metals industry to industrial symbiosis

The non-ferrous metals industry is ready for Industrial Symbiosis. Non-ferrous metals industry has always adopted Industrial Symbiosis principles, along the sector, or together with other sectors. Because of the unavailability of raw materials, recycling has been always a must. Europe metals recycling industry is a real world-leader with a 24% market share (IES, 2018)

Given the intrinsic value and recyclability of non-ferrous metals, innovative solutions have been developed to recover as much metal from waste and by-products from the production process as is economically and technically feasible. Residues from metals production are used as additives in roads, construction or other markets (Eurometaux, 2018).

The European non-ferrous metals industry is already an intricate ecosystem of mining, smelting, transformation, refining, and recycling operations across the continent.

More important, the non-ferrous metals sector is an eco-system in nature. Metal ores consist of various elements that commonly co-exist. Consequently, there is a strong interlinkage between diverse metals during smelting, refining and recycling processes. During the production of a primary metal, other metals can be separated as by-products, constituting a raw material for other productions. At the same time recycling and recovery of metals from other by-products are commonly adopted, providing secondary raw materials.

In the challenge of reducing greenhouse gas (GHG) emissions from Europe’s energy-intensive industries to zero by 2050, the non-ferrous metal industry is a real pioneer. This relatively small industry has already made tremendous progress with a high degree of electrification, circularity and emission reduction.

In the context of IS, a recent review involved Non-ferrous materials and Nanomaterials sectors (Saleh, 2022). It was based on the following considerations: sulfur compounds, which commonly exist in substantial amounts in produced oil, gasoline, diesel, and jet fuel, cause a wide range of negative consequences including pollution, reduced engine efficiency, severe corrosion of pipelines, reactors, and equipment, as well as the poisoning of catalysts. In addition, strict environmental rules and constraints are in place to keep the amount of sulfur in the air to a bare minimum. To achieve this objective, desulfurization or removal of sulfur is applied commonly in most refinery plants. In this review, numerous methods, adsorbents and catalysts used for the elimination of sulfur compounds were investigated. The review presents an overview of the emerging technologies for ultra-deep desulfurization to obtain ultra-low-sulfur fuels. The development of robust adsorbents and nanomaterials with ideal regeneration approaches is required to establish the capabilities of desulfurization processes. This review is expected to provide essential references and future directions for developing desulfurization technologies and materials for practical applications.

The supply risk for some critical rare-earth elements (REEs), which are instrumental in many cleantech applications, has sparked the development of innovative recycling schemes for End-of-Life fluorescent lamps, permanent magnets and nickel metal hydride batteries. These waste fractions represent relatively small volumes, albeit with relatively high rare-earth contents. Rare earths are also present in lower concentrations in a multitude of industrial process residues, such as phosphogypsum, bauxite residue (red mud), mine tailings, metallurgical slags, coal ash, incinerator ash and waste water streams. By involving different sectors, such as Non-ferrous, Metallurgy and critical materials, a recent review (Binnemans, Jones, Blanpain, Van Gerven, & Pontikes, 2015) discusses the possibilities to recover rare earths from these “secondary resources”, which have in common that they contain only low concentrations of rare-earth elements, but are available in very large volumes and could provide significant amounts of rare earths. The success rate is set to increase if the rare-earth recovery from these industrial waste streams is part of a comprehensive, zero-waste, “product-centric” valorisation scheme, in which applications are found for the residual fractions that are obtained after removal of not only the rare earths but also other valuable (base) metals. Meaningful outcomes include:

- Industrial process residues contain low rare-earth concentrations, but volumes are large.
- Bauxite residue (red mud) is an important potential resource of scandium.
- Phosphogypsum is a resource of light rare earths.
- Zero-waste valorisation of industrial process residues is recommended.

High-entropy alloys (HEAs) represent a compelling frontier in material science, characterised by their unique composition of multiple elements typically in near-equimolar proportions. In order to provide an overview of materials and processes for microbial corrosion, materials and concepts on the design and production of antimicrobial deposition layers were studied in a recent review paper (George, 2019). In particular, it aims to comprehensively explore properties and diverse applications of HEAs, with a particular emphasis on their corrosion resistance and potential to mitigate microbiologically influenced corrosion (MIC). The continuous and increasing negative impact posed by MIC on critical infrastructure worldwide demands innovative solutions, and HEAs emerge as promising candidates for addressing this corrosion challenge.

New research achievements related to IS in the non-ferrous metal industry are related to the recovery of lithium from secondary sources by solution combustion synthesis (SCS) as well as electrolysis in ionic liquids (Olaru, 2022), by reaching technical, economic and social results, such as by-products recycling, new business model and new hiring opportunities. Furthermore, an effective ionic liquid (IL)-based method to recover lithium metallic from Li salts, with high efficiency and environmental sustainability was developed. In particular, an environmentally sustainable and efficient method using ionic liquids (ILs) for the recovery of metallic lithium from lithium salts, addressing the high costs and energy demands of current lithium exploitation was developed. This initiative aligns with global recommendations for enhanced circular management of non-ferrous metals, emphasizing the valorization of waste and the recovery of end-of-life products, particularly from spent lithium-ion batteries. Innovations in the LIBs industry, such as the use of stable air salts like BF4-, PF6-, and TFSI-, support the potential of solvent extraction and electrochemical techniques involving ILs as promising alternatives for lithium recovery. In addition, new materials for lithium-ion batteries and hydrogen storage, aiming to reduce the ecological footprint of the transportation industry, were developed. It focuses on optimizing compositions and processes to create competitive materials with less environmental impact and longer life cycles, with an emphasis on recyclability. These new materials are designed based on the concept of using end-of-life products and leveraging improved techniques for obtaining them. On the other hand, it was emphasized the need for efficient, reproducible, and environmentally friendly methods like combustion synthesis to extract lithium from secondary sources, including mining by-products and spent batteries. The aim is to create a sustainable pathway for deriving cathode active material (CAM) precursors from metal compounds, with the lithium oxide produced being convertible into valuable lithium derivatives for use in new batteries and recycling processes.

A vision for the future of non-ferrous metal industry in Europe

The vision for the future of the non-ferrous metal European industry is based on two pillars:

1) the great and growing importance of non-ferrous metal for a carbon neutral and competitive European industry;
2) the intrinsic tendency of non-ferrous metal industry to recycling and recovery metals from by-products.

These two pillars push and pull the development of a new industrial system based on industrial symbiosis approach, characterized by high environmental performance, resource efficiency and innovation, with the aim to further lower the CO2 footprint of European primary production but also to lower import dependency and improve security of supply for strategic metals.

This vision is described in a JRC report for the European Commission (Dessart, 2017), where also challenges and actions needed are presented. This report underlines that technological innovation is crucial to realize this vision. Its contributions relate to generating a better lifecycle understanding of materials, tracing and controlling materials, improving process flexibility and energy efficiency, and facilitating the transition to renewable sources of energy.

4.4.2 European projects in non-ferrous metals sector

The non-ferrous metal is a wide sector, including a huge number of products and by-products, characterized by an immense number of processes and technological solutions aiming at increasing the resource and energy efficiency and improving the environmental impact.

The non-ferrous metal industry has already made big progress on decarbonization, with a high degree of electrification, circularity and emission reduction (VUB-IES, 2018)

Further steps toward the implementation of industrial symbiosis concerns:

- the increase of recycling by means of new technologies for treating, selecting and sorting larger spectrum of scraps;
- the recovery of metals from by-product and wastes, developing new metallurgical processes for improving the exploiting of old and new sources;
- the development of enabling technologies and best practices along all the stages of large-scale existing value chain productions promoting a resource efficient process industry.

Following with European project in this sector, they have been classified as (1) project focused on development of specific technological solution, (2) projects focused on development of new metallurgical processes improving the exploitation of old and new resources, and (3) projects focused on development of general tools and technologies enabling IS.

- **Projects focused on the development of specific technological solutions for enhancing metal recovering from shredder, wastes, industrial residues**

The **SORMEN** project (Grant Agreement ID: 32493, 2006-2008) developed a new technology for the separation of non-ferrous metal Waste from electric and electronic equipment (WEEE) based on multi- and hyper-spectral identification.

This new technology will overcome the shortcomings posed by current methods, which are unable to separate valuable materials very similar in colour, size or shape. The project will provide a reliable technology to automate scrap processing in the recycling sector for non-ferrous metals from WEEE which is nowadays essentially manual, labour intensive and time consuming.

SATURN project (ECO/08/239051/SI2.534294, 2009-2012) was an innovative research project designed to demonstrate the enhanced recovery of non-ferrous metals from waste using advanced sensor sorting technology.

The project has successfully demonstrated how sensor sorting technology can effectively and efficiently separate non-ferrous metals originating from municipal solid waste (MSW) and commercial waste.

The **SHREDDERSORT** project (Grant agreement ID: 603676, 2014-2016) aims at improving the recovery of non-ferrous metals from automotive shredder, in particular aluminium and magnesium, with significant increase of the recycling of these metals, reducing the need of primary production. This represents a major environmental concern due to the much higher energy and emissions of primary production process.

This project aims at developing a new dry sorting technology for non-ferrous automotive shredder. First, shredder will be separated into different metals, based on their conductivity. To this end, a new electromagnetic sensing technique combined with a vision system will be used. In a next step, the light fraction (Al and Mg alloys, with overlapping conductivities), will be alloy-sorted using LIBS. A novel LIBS system design is proposed, enabling upscaling the sorting throughput by one order of magnitude with respect to existing systems.

The **REMOVAL** project (Grant agreement ID: 776469, 2014-2020) will combine, optimize and scale-up developed processing technologies for extracting base and critical metals from Bauxite Residues (Red Mud) form primary aluminum process and valorizing the remaining processing residues in the construction sector.

REMOVAL will process several by-products from the aluminium sector and from other metallurgical sectors in Europe (SiO_2 by-products, SPL, fly ash and others). The different waste streams will be combined to allow for optimal and viable processing in different technological pilot nodes.

REMOVAL will gather key sectors like the non-ferrous metal and cement sectors in order to secure a true industrial symbiosis through a top-down approach considering also legislation and standardization at European level in order to facilitate the implementation of the most promising technical solutions.

TRANSECOTEH (TRANSECOTEH, Structural funds; 01/09/2016–31/01/2020) “Promotion of eco-efficient non-conventional technologies for the recovery of useful metals from industrial waste by establishing partnerships for knowledge transfer with companies” project promoted an eco-efficient technology for the recovery of industrial waste containing non-ferrous metals by transferring it to companies, in order to obtain value-added products through innovative technologies with significant impact on reducing environmental pollution and complying with legislative requirements. <u>Objectives</u>: Reducing the impact of polluting activities on human health and environment, by increasing the recovery potential of non-ferrous, precious and critical metals contained in waste and their reintroduction into the economic circuit. Results:

- Partnership established interested in developing common applied research in the field of advanced technologies, with applications in environmental greening;
- Industrial waste recovery installation for non-ferrous metals, for the recovery of useful, precious and critical metals through innovative technologies in ecological conditions and maximum efficiency, with major socio-economic impact;
- Increased innovation and technological development of the companies involved in the project;
- Increased competitiveness of the companies by applying innovative waste processing technologies on a less developed market in Romania;
- Increased level of knowledge of employees from the companies involved in the project, in the field of ecological processing of industrial metallic waste, following knowledge transfer from IMNR;
- Development of the technological transfer capacity of IMNR by cooperating with companies and establishing long-term partnerships.

Enhancing the Rare Earth Elements Research and Innovation Capacity of Türkiye (Enhancing the Rare Earth Elements (REEs) Research and Innovation Capacity of Turkey , SMEs, Manufacturing Industry, Entrepreneurs, R&D Centers, Investors, Public Institutions; 21/07/2022-20/07/2024). This project aims at increasing global competitiveness with the added value of REEs by enhancing the national REEs-related R&D capacity in Türkiye. In line with the result areas, capacities of the REE R&D centres will be improved and business networks of the REE R&D centres will be enhanced. Supporting the establishment of a sustainable REE supply chain for economic development of Türkiye and increasing its competitiveness with the added value of REEs in the global scale. Objectives: consultancy for elaboration of business studies to implement mining and metallurgy processes for valorization of rare earth elements from ores discovered in Turkish deposits. Meaningful outcomes: Metals extraction, rare earth recycling, new business models, new job opportunities.

MW4REMAM (MW4REMAM, Horizon Europe-ERAMIN3; 15/04/2022-31/12/2024). Rare Earths Elements (REE) are essential materials in connected and electrical technologies, and the transition to a decarbonisation and greener economy, due to their unique properties making them suitable for use in various automotive, electronics, industrial, power generation, and other applications as for example permanent magnets, sensors, catalysts, rechargeable batteries, etc. Technical innovations, including advanced physical separation techniques, new treatment for an increased recovery of valuable metals and technologies are needed to recover metals from residues by physical, chemical, biological methods or combinations thereof. Objectives: development of an innovative technology for efficient recovery of both rare earth metals and plastics from end-of-life WEEE and urban mines. Then re-use them as raw material for fabrication of plastic-RE composite filaments and create new magnetic components via additive manufacturing. Meaningful outcomes: WEEE recycling, digitization of magnets manufacturing using software for NdFeB redesign, new business model for urban mines valorization.

RELiEF (RELiEF, Horizon Europe; 01/07/2022-30/06/2025) is aimed at revolutionizing lithium (Li) recycling by focusing on secondary raw material sources, a largely untapped area in current recycling technology. With a goal to reduce the 27.33% of unrecovered Li from waste, which significantly impacts global Li production, RELiEF proposes an integrated recycling facility designed for continuous processing to produce high-quality, battery-grade materials. The project anticipates reducing Li waste by over 70%, converting it into valuable battery materials. It will demonstrate the integrated and continuous process up to battery precursor recovery at Technology Readiness Level (TRL) 5, and a closed-loop process for battery active material at TRL 4. This process is expected to yield 1.5 – 2.5 kg/week of battery active materials. Additionally, RELiEF plans to develop a new business model that prioritizes environmental and social sustainability in materials acquisition and processing. This initiative aims to reduce the EU's dependence on imported battery chemicals and raw materials. Objectives: RELiEF aims to develop an integrated Li recycling unit to produce battery active materials from secondary and lowgrade Li sources, to reduce the EU dependency on importing battery materials to a nominal level and to minimize the Li waste which is currently not properly accounted for and monitored. Beyond this, a successful sustainable business model will be developed and demonstrated at TRL 4-5 (weekly 1.5Kg-2.5Kg kg of repaired LFP & Li-M anode) at EE's pilot plant site. Meaningful outcomes: Technical – processing and refining of raw materials; recycling technologies, increase capacity to re-process recycled lithium from spent batteries; Economic – decreasing dependency of Europe on imported battery chemicals and raw; increasing global competitiveness of EU battery ecosystem; new business opportunities and models; Social – impact on the workforce by creating additional jobs.

➢ **Projects focused on development of new metallurgical processes improving the exploitation of old and new resources**

The overall objective of **SOLCRIMET** project (Grant agreement ID: 694078, 2016-2021) is to develop a new, metallurgical approach – i.e. solvometallurgy – that can be applied to different types of pre- and post-consumer waste in order to recover the following critical metals: the rare earths, tantalum, niobium, gallium, indium, germanium and antimony. This processing must be environmentally friendly, economically viable and produce metals of acceptable purity. The achievement of the main objective is built on four sub-objectives:

- New routes for dissolving metals and alloys in organic solvents;
- New ways to separate metal chlorides based on differential solubility in organic solvents;
- New paths to purify critical metals using two mutually immiscible organic solvents;
- New techniques for refining critical metals in an electrolytic cell using organic solvents.

Achieving these four sub-objectives will lead to a new paradigm in recycling and completely alter the whole concept of extracting critical metals from different forms of waste.

METGROW+ project (Grant Agreement ID: 690088, 2016-2020) aims at solving bottlenecks in the European raw materials supply by developing innovative metallurgical technologies for unlocking the use of potential domestic raw materials. Within this project, both primary and secondary materials are studied as potential metal resources. Economically important nickel-cobalt deposits, low grade polymetallic wastes and iron containing sludges (goethite, jarosite ,etc.) which are currently not yet being exploited due to technical bottlenecks are in focus.

METGROW+ targets innovative processes to extract important metals including Ni, Cu, Zn, Co, In, Ga, Ge in a cost-effective way.

METGROW+ developed pyro-, hydro-, electro-, bio-, solvo- and ionometallurgical unit operations, as well as residual matrix valorisation technologies, to valorise EU's low-grade, polymetallic primary and secondary resources. Pretreatment metallurgical unit operations were adapted to make them applicable for low-grade complex polymetallic, primary and secondary resources. New metallurgical unit operations for metal extraction were developed. The new unit operations are: "hydroflex", bioleaching, solvoleaching and "plasma-pyro".

As project main output, a toolbox for metallurgical systems development is created, which combines individual unit operations to obtain the most cost-effective and environmentally-friendly flow sheet for a given low-grade resource.

The METGROW+ toolbox boosts the European mineral extractive and processing industry, since it triggers the cost-effective exploitation of Europe's domestic low-grade primary and secondary resources. The toolbox provides a feasible, sustainable, cost-effective set of processes, ranging from upstream activities to downstream activities including wastewater treatment with biosorption and biological sulfate reduction. In addition to the direct impact in metal exploitation and production rates, the use of the METGROW+ toolbox has a cross-sectorial impact in the metal-related European industry, since it produces a set of process steps that cover the value chain. Since the toolbox addresses technological, environmental, economic and social assessment, different levels of the European scenario can benefit from the information provided by the tool: public bodies can retrieve information for policy making and about social impact (policy level), companies can be aware of best approaches for sources exploitation (market/business model level), whereas the community can learn about new trends and technology performance (technological level).

NEW-MINE project (Grant Agreement ID: 721185, 2016-2020) develops and integrates cutting-edge, eco-friendly Enhanced Landfilling Mining, ELFM, technologies to valorise Europe's 150,000– 500,000 landfills, thereby recovering resources (materials, energy, land), while mitigating future environmental and health risks associated with landfills as well as avoiding enormous landfill remediation costs. Spill-over of technologies to other sectors (e.g. treatment of fresh waste, mining sector, use of secondary raw materials in the building sector) is considered to be natural.

The technological innovation follows a value-chain approach, from advanced landfill exploration, mechanical processing, plasma/solar/hybrid thermochemical conversion and upcycling, while the multi-criteria assessment methods allow to compare combined resource-recovery/remediation ELFM methods with the "Do-Nothing", "Classic remediation" and "Classic landfill mining with (co-)incineration" scenarios.

NEW-MINE trains 15 early-stage researchers (ESRs) in all aspects of landfill mining, in terms of both technological innovation and multi-criteria assessments. By training the ESRs in scientific, technical and soft skills, they become highly sought-after scientists and engineers for the rapidly emerging landfill-mining and broader raw-materials industries of Europe.

COM℗TRANS (COM℗TRANS, M-ERA.NET 2020; 01/06/2021–31/12/2023) "Composites Based on Compositionally Complex Alloys for Transportation Industry". The goal of the project is the development of new metal matrix composites based on low weight compositionally complex alloys (CCA) and ceramic particle reinforcement for brake systems in transportation industry. The new matrix alloy will provide increased strength and higher temperature operation for the developed composite material. The technology based on the new composites will provide solutions for the replacement of conventional methods by addressing main issues: maximize the operation efficiency, lower the fabrication costs and lower the polluting emissions. The newly developed materials will present high strength and stiffness to weight-ratio and will be easily recyclable. Objectives: Selection of appropriate composite matrix compositions based on low weight compositionally complex alloys; Achievement of laboratory technology for synthesis of selected alloy compositions; Achievement of laboratory technology for composite material synthesis; Technology and product validation; Assessment of the environmental impact of the technology and final product. Results:

- Selection of appropriate composite matrix compositions based on low weight compositionally complex alloys;
- Achievement of laboratory technology for synthesis of selected alloy compositions;
- Achievement of laboratory technology for composite material synthesis;
- Technology and product validation;
- Assessment of the environmental impact of the technology and final product.

PHEIDIAS (PHEIDIAS, 2022-2024) project aims at upscaling an innovative hydrometallurgical process from TRL5 to TRL8 for the recovery of PGMs from spent catalysts. It is an innovative chemical process for recovery of platinum metals from spent automotive catalysts and re-use in the automotive sector Objectives: Building up a commercial network between recycling plants, suppliers and end customers of recovered platinum metals and catalysts. Meaningful outcomes: By-product recycling, new inter-regional business network.

AHEAD (AHEAD, Romania's National Recovery and Resilience Plan; 01/07/2023-30/06/2026). For many years people are aware of the existence of natural materials and elements with antimicrobial behaviors (e.g. silver and copper) which they try to employ for hygiene and protective applications with a certain level of success that are enabled via nanoparticles or metal ions activity. Despite such antimicrobial agents demonstrate their influence even at relatively low concentrations, their content must be high enough to be effective as an antimicrobial material. But very often, at high concentration of antibacterial elements physical and mechanical properties of material tend to rapid degradation and decrease. Thus, it is challenging nowadays to obtain surfaces with both high antimicrobial and bio-corrosion efficiency and high wear performance in extreme conditions. Fundamental research on the new developed HEA coatings will be performed ranging from prior thermodynamic calculations, simulations, and prediction of mechanical and corrosion properties by machine learning means to the fabrication of coatings and experimental characterisation of their physical and mechanical properties followed by bio-corrosion behaviours tests and proof of concept for anti-microbial properties. Objectives: The aim of this project is to develop coatings with enhanced physical, mechanical and biocorrosion resistant properties to increase significantly their performance and long lifetime. This is expected to be achieved by developing a new concept of biocorrosion inhibitor metal atoms embedded into the matrix of high-entropy alloy (HEA) material composed of 5 or more elements selected based on modelling and simulation methods. Meaningful outcomes: Compositional screening of materials for the best mechanical, bio-corrosion and antibacterial properties by calculations and machine learning tools; Fabrication of antimicrobial samples with predicted elemental composition and structure.; The elemental composition, structural characterisation and mechanical properties evaluation; Optimisation of fabrication parameters and validation of the improved HEA-based antimicrobial materials for designated applications.

- **Projects focused on development of general tools and technologies enabling industrial symbiosis**

SYMBIOPTIMA project (SYMPIOPTIMA, H2020-EU.2.1.5.301 September 2015- 28 February 2019) aims at improving the sustainability of contemporary industrial processes by developing and implementing a new paradigm whereby critical resources such as materials, energy, waste and by-products can be coordinated more efficiently between Production Units.

The paradigm, adopted by the SYMBIOPTIMA project, was 'human-mimetic symbiosis' which takes its inspiration from the functioning of the human body. This approach rethinks and reuses production resources across diverse industries, and even sectors, for increased efficiency with fewer adverse environmental impacts.

SYMBIOPTIMA developed an integrated Energy and Resource Management System (ERMS), which offers tools for production scheduling and demand response management and for Life Cycle Sustainability Assessments (LCSAs). It also created hardware for modular 'plug and play' monitoring of production plants, as well as an integrated toolset for all thermal energy sources, flows and sinks.

The **ZeroWaste Cluster** is a cooperation of eight different Network of Infrastructures (NoI) which are projects funded by the EIT RawMaterials[1]. A NoI type of project is generally an accelerator aiming at mapping services to provide overview and access to facilities and expert knowledge available within the consortium including pilot plants, technical centres and analytical and modelling infrastructure.

Vision of the Zero Waste Cluster.

Material recovery from low grade, complex ores, wastes and residues requires an integrated approach combining different technologies for pretreatment, metal extraction and residue valorization. The Zero Waste Cluster wants to create services offered by a virtual pool of state-of-the art infrastructure and expertise present at EIT Raw Materials partners, which are front-runners in sustainable innovation in the different technologies and supporting expertise, in order to facilitate access to capital-intensive infrastructure and expertise across the value chain.

Mission of the Zero Waste cluster

The different networks in the Zero Waster Cluster group state-of-the-art infrastructure and expertise related to a specific field of pretreatment, extraction, valorization or supporting expertise such as sustainability assessment within the circular economy. A web-based platform aims at providing tailored solutions for any customer looking for specific infrastructure or expertise, making use of our Zero Waste metallurgical toolbox.

General objectives of the zero-waste cluster are:

- Gather waste stream owners from the supply side and material resource users from the demand side to meet intermediary technology SMEs and RDIs bridging gaps between both sides of the value chain.

[1] EIT RawMaterials, initiated and funded by the EIT (European Institute of Innovation and Technology), a body of the European Union, is the largest consortium in the raw materials sector worldwide. Its vision is to develop raw materials into a major strength for Europe. Its mission is to enable sustainable competitiveness of the European minerals, metals and materials sector along the value chain by driving innovation, education and entrepreneurship.

- Provoke industrial innovation, by offering access to key infrastructures and services for the exploitation of complex, low-grade ores and waste streams.
- Stimulate smart specialisation by the partners by inventorying available infrastructure within the network and Europe to identify gaps to be filled by defining new pilot actions.

The zero-waste cluster includes the following network of infrastructures.

- INSPIRE (2016-2019), “Intensified Flow Separator Infrastructure and Expertise Network”.
  Aims to develop breakthrough Process Intensification technologies for continuous separation of critical materials.
- PREFLEX (2016-2018), “Pre-treatment and Physical separation”.
  Aims to boost innovation in the raw materials sector through collaboration by establishing a Europe-wide network that hives the infrastructure and skills regarding Pre-treatment and Physical separation.
- BIOFLEX (2016-2018), “Flexible Biometallurgy Infrastructure and Expertise network”.
  Aims to bring together partners with infrastructure and expertise in bio-metallurgy. Biometallurgy includes bioleaching of metals from ores and waste, biosorption of metals from liquid streams and leachate, bio-precipitation of metals and bio-electrochemistry of metals.
- ELECTROFLEX (2017-2020), “(Bio)Electrochemical extraction and recovery of metals from low grade ores and residues”.
  Provides easy access to equipment and expertise via a web-based tool and a central point-of-contact, matching demand and offer.
- PYROFLEX (2016-2018), “network on pyrometallurgical expertise and infrastructure for residue treatment”.
  To deal with complex low grade residues, allowing the recovery/removal of valuable elements present in low concentrations, as well as to produce a clean slag by hot stage engineering and controlled solidification for subsequent valorization.
- SOLVOFLEX (2016-2018) “Solvometallurgy Infrastructure and Expertise Network”
  to providing services to customers for the implementation of innovative, sustainable business and cooperation models for recycling and/or exploitation of raw materials from end-of-life products, as well as supporting companies and to facilitate the exploitation of European secondary resources via collaboration (software, databases, competences, infrastructures, instrumentation, best practices, etc.) implementing industrial symbiosis and the circular economy
  RESIDUFLEX (2016-2018) “infrastructure and technology network on residue valorization”.
  aims to increase the number of residues that can be treated by proving the feasibility on the lab scale as well as to detecting opportunities for upscaling, and to enhance the recovered/generated value.
- SSIC (2016-2018), Sustainability Support and Information Centre
  provides information on the sustainability of material stocks, evidence on resource efficiency, analysis of critical raw material savings, guidance on innovation options for life cycle impact hotspots, sustainable up-scaling scenarios, socio-economic costs and benefits, job creation potential of new technologies, market potential, recyclability benefits of new waste valorization options.

4.4.3 The Aluminium sector

According to (Aluminium E. , EU Strategies on Energy Sector Integration & Hydrogen, 2020), European Aluminium represents the entire value chain of the aluminium industry in Europe. Protecting the competitiveness of European aluminium producers and industrial energy consumers will have to be a guiding principle across all envisaged actions under the upcoming strategies. Europe should urgently reflect on how to reinforce its strategic autonomy in global value chains, preserve existing industrial assets and reshore the production in Europe instead of relying on carbon-intensive imports. Industries in Europe need today more than ever an enabling framework to be more energy-efficient, competitive, circular, and sustainable to deliver and invest in climate neutrality while operating in a free and fair-trade environment.

The European aluminium industry started its collective journey towards sustainability long ago. In 2015, we launched our Sustainability Roadmap Towards 2025. Complementing existing legislative requirements, the Roadmap outlines the industry's sustainability objectives in the areas of production, applications and society. The Roadmap is complemented by the Vision 2050 for a low carbon industry by 2050 and the Circular Aluminium Action Plan, the sector's strategy for achieving aluminium's full potential for a circular economy by 2030. The new Circular Economy Action Plan should create the right incentives to promote circular business models to take advantage of the enormous potential that lies ahead for the aluminium industry in Europe. European Aluminium's policy recommendations aim to ensure – firstly - circular material handling along the entire value chain starting with the design of products and – at the same time - to create adequate incentives for circular solutions and products, to stimulate investment in collection and sorting and to foster innovation of production processes (Plan, 2020). This Action Plan builds on the aluminium industry's Vision 2050, with a focus on recycling and provides policy recommendations for the sector to achieve full circularity. Aluminium is a circular material, capable of being recycled multiple times without losing its original properties (lightness, conductivity, formability, durability, impermeability and multiple recyclability). Aluminium recycling rates are among the highest of all materials. In Europe, recycling rates are over 90 percent in the automotive and building sectors, and 75 percent for aluminium cans. These recycling rates for aluminium are achieved due to well-developed collection systems – especially for vehicles reaching their end-of-life, building scrap and used beverage cans; high scrap sorting rates; low losses when aluminium is re-melted to recycled metal; and a high-quality end product which can be used in high-value applications. The result is a system driven by the intrinsic value of the metal. Recycling aluminium in Europe can thereby avoid high CO2 emissions by replacing carbon-intensive aluminium imports. The aluminium recycling process requires only 5 percent of the energy needed to produce the primary metal, resulting in greenhouse gas emissions of 0.5 tonne CO2 eq/tonne recycled aluminium (gate to gate). It does not include the inherent carbon footprint of the aluminium scrap. The aluminium industry is keen to seize the opportunities presented and to drive the changes needed. It is important to ensure that all end-of-life aluminium products are collected and recycled efficiently in Europe to maximise aluminium recycling rates and to keep the material in active use. Policy support will be needed to enable research, to coordinate measures along the value chain, to influence market demand for circular solutions and consumer awareness, to make investments economically viable, and to develop the business models required to underpin them. European Aluminium calls upon the institutions of the European Union to boost the circular economy and to recognise multiple recycling as key to preserving resources, mitigating emissions and spurring economic growth in Europe.

Building a sustainable industry is a collective effort and partnerships are essential. In 2016, European Aluminium joined the Aluminium Stewardship Initiative, a multi-stakeholder, standards-setting and certification body launched to foster the responsible production, sourcing and stewardship of aluminium across the value chain. In 2021, European Aluminium also joined CSR Europe's Pact for Sustainable Industry to scale up the impact of individual efforts made by companies, industry federations and EU leaders towards a Sustainable Europe 2030 in line with the EU sustainability objectives (Europe, 2021). The progress towards our Sustainability Roadmap objectives is regularly tracked via a broad set of Sustainable Development Indicators, using data collected from aluminium companies operating in Europe. European Aluminium is committed to transparency and regularly publish public reports and verified data on our sustainability performance. In addition, in 2021, the comparison of the achieved progress against the Roadmap's objectives in a broad mid-term review was carried out (Aluminium, ALUMINIUM IN ACTION SHAPING SOLUTIONS FOR A SUSTAINABLE SOCIETY, 2021). In 2021, European Aluminium conducted a thorough review of the Roadmap with our members to assess progress towards the targets and identify the next steps and tools required to help reach the industry's sustainability objectives. The exercise confirmed the aluminium industry's efforts in establishing a sustainable, decarbonised and circular Europe, and paved the way for even more ambitious targets in a series of areas.

On the other hand, concerning the climate change issue, the new EU's 2030 GHG emission reduction target of -55% will have profound implications on the competitiveness of the European Aluminium industry. Such enhanced climate ambition must be accompanied by a robust enabling framework that supports our industry's transition to climate neutrality. Europe's transition to a low carbon economy can only be achieved with more aluminium, given the growing demand for light and circular metals, which are essential for clean technologies. On this subject, the sector recommendations for the Fit-to-55 package, considering the energy-intensive nature of processes, particularly the electricity-intensive nature of producing primary aluminium, and the cost implications of higher CO_2 prices across the entire value chain stemming from the revision of the ETS and other pieces of the energy and climate framework. Also, it has been underlined the need for supportive policy and regulatory measures to accelerate the decarbonisation of the energy system and increase the availability of low carbon energy at globally competitive price (Aluminium E. , Our proposals to the EU's "fit for 55% package-For a low-carbon, circular and green aluminium industry in Europe, 2021). The commitment of European Aluminium sector to decarbonisation by 2050 was first established several years ago, but commitments only matter when they are backed up by concrete plans to act. With the publication of 'Net-zero by 2050: Science-Based Decarbonisation Pathways for the European Aluminium Industry,' the Aluminium community has taken the next step, by moving beyond to focus on the journey itself. Since aluminium is both a significant source of greenhouse gas emissions today and a strategic material for the clean energy sector of tomorrow, the stakes are high. Taking alignment with the IPCC's 1.5°C scenario as its north star, a recent study provides a comprehensive overview of the technological solutions that will be needed across the entire European aluminium value chain and it provides recommendations for a policy framework allowing various solutions to deliver on their potential (Aluminium R. a., 2023). The overarching objective of this study is to align the European Aluminium sector with the Intergovernmental Panel on Climate Change's (IPCC) 1.5°C by 2050 scenario, while offering a comprehensive overview of the different steps needed to reach this ambitious goal. In particular, the study aims at: demonstrating the industry's dedication to operational decarbonisation; balancing the benefits of aluminium usage with insights into production and manufacturing; providing a sectoral framework for member companies to establish their decarbonisation pathways; offering policy recommendations to create an enabling environment for achieving a 1.5°C-aligned trajectory. Finally, the analysis presented demonstrates that decarbonising the European Aluminium Sector will require ambitious actions. By 2030 and 2040, the emissions profile of European aluminium production should be cut by at least 37% and 78%, respectively. In this context, to support the development of a robust common methodology, assessing the carbon content of products and helping decarbonise the value chain on a global scale, the European aluminium value chain is committed to develop a holistic and global approach to produce a sustainable product from low-carbon and circular to responsibly sourced and manufactured aluminium (European, 2023). Nevertheless, its decarbonisation and sustainability efforts are often undermined by market distortions, mainly caused by China. For this reason, European Aluminium Industry is convinced that a competitive global market-place needs free and fair trade while. In this context, to achieve the aims of the Green and Digital transitions and to allow for a long-term sustainable growth, it developed the Position Paper, expressing support for the Critical Raw Materials Act (CRMA), as a crucial initial step towards a comprehensive value chain approach for Europe's strategic resilience and sustainable growth (Aluminium E. , Critical Raw Materials Act, 2023). This position paper urges the addition of aluminium to the list of "Strategic Raw Materials" due to its significance in the twin transition, defence sectors, and potential global supply/demand imbalances. Furthermore, the paper emphasizes the need for stakeholders involvement, complementarity with the Net Zero Industry Act, more ambitious CE provisions, and the boost of investments through new financing mechanisms to safeguard Europe's industrial base and to achieve the goals of the Green and Digital transitions. By summarising, the main objectives are: 1. Adding aluminium to the list of "Strategic Raw Materials"; 2. Additional considerations for aluminium and its importance as a Strategic Raw Material; 3. Involving industry stakeholders in the European Critical Raw Materials Board; 4. Ensuring complementarity with the Net Zero Industry Act; 5. Promoting more ambitious circular economy provisions 6. Boost investments by gearing up new financing mechanisms.

4.4.3.1 Projects on Industrial Symbiosis deeply involving the Aluminium sector

The project related to the aluminium sector in the Industrial Symbiosis is:

- **SCALE** (Alumina, Chemical sectors) (SCALE, H2020, 2016-2021) Objectives: To demonstrate a novel value chain for production of Sc and Al-Sc alloys from European secondary resources.
    - The SCALE project develops the technology to extract Scandium from Bauxite Residue and upgrade it to commercial product, setting the foundation for multi-level valorization of BR leading to a zero-waste solution.
    - The SCALE project develops the technology to extract Scandium from TiO2 by-products and upgrade it to commercial product, setting the foundation for an additional European Sc-resource
    - SCALE develops new technological routes, by-passing existing expensive (and in some cases potentially dangerous for the human health) processing steps like Sc fluorination (IV) from ultra-pure Sc2O3 with gaseous HFor Sc reduction through calciothermic reduction of ScF3 (V) and Sc-Al alloying from metallic Sc (VI). New connections in the processing chain are established through innovative SCALE technologies, which allow direct crystallization of ScF3 from Sc strip

solution, direct electrolysis of Sc_2O_3, and direct production of Sc-Al master alloy from Sc_2O_3 or ScF_3.

Short Description: The main aim of the SCALE project is the efficient exploitation of EU high concentration scandium containing resources including bauxite residues (100-150 ppm) resulting from alumina production and acid wastes (50-100 ppm) from TiO_2 pigment production to develop a stable and secure EU scandium supply chain to serve the needs of EU aerospace and high tech industry. This will be achieved through the development of a number of innovative extraction, separation, refining and alloying technologies that will be validated in an appropriate laboratory and bench scale environment to prove their technical and economic feasibility. The industrially driven SCALE consortium is led by 2 European alumina refineries (AoG, AOS) and one TiO_2 pigment producer (TRONOX) who are joined by the key Sc producers and end-users in Europe like II-VI (Sc_2O_3 producer / optical applications), LCM (REE metal producer) and KBM (Al-Sc alloy producer).

Meaningful Outcomes: Industrial Pilot scale demonstration for Sc extraction from Bauxite Residue and Acid Waste.

4.4.3.2 Projects on Industrial Symbiosis and Energy Efficiency deeply involving the aluminium sector

The projects related to the aluminium sector in the Industrial Symbiosis and Energy Efficiency are:

- **RemovAL** (REMOVAL, H2020, 2018-2022) Objectives: RemovAL is a holistic, scale up project. The ambition of RemovAL is straightforward: to overcome environmental issues and technological barriers related to aluminium industry, by combining and advancing existing technologies for the sustainable processing of BR, SPL and other by-products generating revenue. The following processing technologies form the nodes through which different paths can be drawn, depending on waste characteristics, availability and logistics among waste producers and end-users. The objectives of this project are to deliver and validate a complete feasibility study for each of the 3 alumina producers and the 1 legacy site owner in the consortium detailing the optimum processing flow sheet for valorising the produced Bauxite Residue (BR) along with other industrial by-products, taking into consideration waste characteristics, logistics and potential for symbiosis with other plants in the geographical vicinity . Following this, each plant will be able to implement its own BR valorisation plan. Short Description: The answer to the current Raw Material supply challenge faced today in Europe, lies in technological innovations that increase the efficiency of resource utilization and allow the exploitation of yet untapped resources such as industrial waste streams and metallurgical by-products. One of the key industrial residues which is currently not or poorly valorised is Bauxite Residue (BR, more commonly known as "red mud") from alumina refineries. Bauxite residue reuse solutions do exist as stand-alone but pooling them together in an integrated manner is the only way to render bauxite residue reuse viable from an economical point of view and acceptable for the industry The RemovAl project will combine, optimize and scale-up developed processing technologies for extracting base and critical metals from such industrial residues and valorising the remaining processing residues in the construction sector. In term of technological aspects, RemovAl will process several by-products from the aluminium sector and from other metallurgical sectors in Europe (SiO2 by-products, SPL, fly ash,and others). The different waste streams will be combined to allow for optimal and viable processing in different technological pilot nodes. The technologies and pilots in most cases have already been developed in previous or ongoing projects and through RemovAl they will be pooled together and utilized in a European industrial symbiosis network. In term of societal or non-technological aspects, RemovAl will gather key sectors like the non-ferrous metal and cement sectors in order to secure a true industrial symbiosis through a top-down approach considering also legislation and standardisation at European level in order to facilitate the implementation of the most promising technical solutions. Meaningful Outcomes: It starts with technologies that have been at least validated at lab scale (TRL 4 or higher) combines and optimizes them for the raw materials available in the project and delivers technologies demonstrated in actual industrial environments (TRL 7-8). Most of its products have well established markets (cement, lightweight aggregates, mineral wool) or end-user industries (ferro alloys, cement raw materials, alumina, rutile, REE oxides, etc.) ensuring a direct applicability of the project results. There are also some innovative processing reactors (Microwave prototype kiln) or innovative products (soil stabilizer, new inorganic binders) which yet have not been applied/produced in large scales (but have been tested at scales up to 1t/day) and which further enhance the project's innovation and added value potential.

- **AlSiCal** (AlSiCal, H2020/2014-2020 under grant agreement n° 820911, 2019-2023) is an ambitious research and innovation effort to make the mineral and metal industry more sustainable and environmentally sound. The project will further research, develop and de-risk a ground-breaking concept: the patented Aranda-Mastin technology. By integrating CO_2 capture, this technology enables the co-production of three essential raw materials (alumina, silica and precipitated calcium carbonate), using new resources – e.g. anorthosite, abundantly available worldwide – whilst generating ZERO Bauxite residue and ZERO carbon dioxide (CO_2) from production. Objectives: AlSiCal overarching objectives are:
    - Position the European Union at the forefront of innovation for the Green Shift for the mineral and metal industry;
    - Secure European sustainable production of alumina, silica and precipitated calcium carbonate by researching, developing and de-risking a ground-breaking technology for ZERO Bauxite residue and ZERO CO2 emissions from their co-production;
    - Unlock substantial reserves of new resources within the European Union – and from worldwide available resources – that can complement or substitute today's worldwide production of alumina under sustainable principles.

  Meaningful Outcomes: The experimental setups are being designed and built at present, and will become cutting edge facilities in hydrometallurgy and CO2 utilization innovation for more sustainable industry. The Aranda-Mastin technology has large potential to expand towards varied process sources besides anorthosite, for which, in addition to different anorthosite qualities, alternative sources are being screened by our experts. Our modelling teams (both at reactor and process level) and LCA analysts are already getting started with data gathering. Last, but not least, we are aware of the expectations and need for information, for which we dedicate special efforts on keeping informed stakeholders, collaborating organizations and society. Thus, dissemination and communication aspects are taken care and we have already developed the project website, first brochure, social media accounts, first newsletters and the two first interviews by non-scientific publishers.

- **ReActiv** (ReActiv, H2020, 2021-2024) project will create a novel sustainable symbiotic value chain, linking the by-product of the alumina production industry and the cement production industry. Bauxite residue (BR) is the main by-product of the alumina sector produced at rates of 7 million tons per year in EU, while recycling rates are less than 100 thousand tons per year respectively. In ReActiv modification will be made to both the alumina production and the cement production side of the chain, in order to link them through the new ReActiv technologies. The latter will modify the properties of the industrial residue, transforming into an active material (with pozzolanicor hydraulic activity) suitable for new, low CO2 footprint, cement products. In this manner ReActiv proposes a win-win scenario for both industrial sectors (reducing wastes and CO2 emissions respectively). Objectives: To achieve its objectives the ReActiv project brings together the global leader in cement production with the biggest alumina producers along with top research and technology centers with significant expertise in the field. Furthermore, the European alumina association and the international Aluminium institute are participating in the project to safeguard the industrial dissemination and deployment of project results. Meaningful Outcomes: The methodology developed under ReActiv can be replicated in by-products of other industrial sectors as well. To this end the project will seek to include in modelling and/or labscale environment other by-products in the developed flowsheets.
- **H2Glass** (H2Glass, Horizon Europe; 2023-2026) project will bring together 23 partners from around Europe to create a new technology stack that glass and aluminium manufacturers can use to achieve complete hydrogen combustion. Specifically, the project will address the challenges related to emissions of nitrogen oxides and high flame propagation speed, process efficiency and supply of hydrogen for on-site demonstrations. Digital twin techniques will be used to assess risk-based predictive maintenance. Another project feature is the demonstrator in the aluminium industry to prove the transferability of underlying models to similar energy-intensive industries. Objectives: The glass industry will have to be completely decarbonized in the next 30 years. The lifetime of a glass furnace is about. 12-15 years. So it is urgent to start innovating because the year 2050 is only 2 furnaces away. H2GLASS aims to create the technology stack that glass manufacturers need to (a) realize 100% H_2 combustion in their production facilities, (b) ensure the required product quality, and (c) manage this safely. H2GLASS will address the challenges related to NO_x emissions and high flame propagation speed, process efficiency, and supply of H_2 for on-site demonstrations. Digital Twin techniques will be critical for risk-based predictive maintenance, optimized production control, and combustion system control. Hydrogen will be supplied by a portable electrolyser co-funded by the industrial demonstrators, and the oxygen produced will be reused in the process. The H2GLASS technologies and design solutions will be validated up to TRL 7 on 5 industrial demonstrators from 3 segments (container glass, flat glass and glass fibre), which together represent 98% of the current glass production in the EU. The expertise of partners such as Steklarna Hrastnik, PTML Pilkington, Owens Corning and Stara Glass representing the State Of The Art (SOTA) in the use of H_2 in the glass process will be an asset for the H2GLASS Consortium. A demonstrator for the Aluminium Industry (HYDRO) will prove the transferability of the basic solutions and underlying models to EIIs that have similarities with the glass manufacturing process, thus

strengthening the impact of the project. In EU the Glass and Aluminium industries employ >400.000 people in Europe, generate > 3.5B€ and emit ca.21.5 Mt CO_2e. The innovations generated by H2GLASS will potentially create 10.000 new jobs and unlock 1 - 5B€ revenues for glass technology deployment, >17B investments and 200.000 new jobs for green H_2, and cut emissions by ca.80%. Meaningful outcomes: Developing the technology stack that will enable 100% H_2 combustion in the glass industry; Raise public understanding on H_2 technology as solution for decarbonising industrial processes; Transfer technology to other EU energy-intensive industries.

4.5 Mineral Sector

4.5.1 State of the art of the Industrial Symbiosis in the minerals sector

The New Circular Economy Action Plan (CEAP) was published in March 2020 (Commission, Changing how we produce and consume: New Circular Economy Action Plan shows the way to a climate-neutral, competitive economy of empowered consumers, 2020). It brings together a holistic strategy on how to tackle and how to address the challenge ahead. With regard to the actions reported in the CEAP, there are some directions actions that have a direct impact for the minerals sector, such as:

- Launch of an industry-led industrial symbiosis reporting and certification system for 2022.
- Strategy for a sustainable Build Environment (2021).
- Regulatory Framework for the certification of carbon removals (2023).

Multiple Mineral solutions illustrate how this recovery happens and the sectors that can benefit from these innovations (e.g. **bentonite as valorising tailing wastes and clean processed water**; **FineFuture**, **RE-BIOP-CYCLE)** . As recovery processes can be very energy intensive, environmental and land use related aspects are also particularly relevant in that environmental gains may also occur and, moreover, land space can be liberated and reused for new purposes and services as has been demonstrated in the publications: 1. Contribution of Industrial Minerals in Circular economy (2018) as well as 2. EuLA Innovation report (2018). These publications and some of the case studies presented below illustrate how the industrial minerals can be solution providers to address social challenges of energy transition, CO_2 reduction, energy transition, resource recovery; waste valorisation for CRM recovery and address sustainability holistically. Other examples illustrate how the past historical waste can be a source to supply the demand for battery raw materials or for the energy transition raw materials for example (example of FineFuture; STOICISM,). The work of the industrial minerals sector cannot stand alone as the cross cooperation and industrial symbiosis to address societal challenges such as industrial symbiosis and cross sectoral cooperation to reduce the CO_2 and resource footprint is also illustrated with some of the projects below (EPOS – cross process industry; lime - steel). Finally, availability of data and information on secondary materials as well as a harmonised legislative framework within the EU appear to be crucial for the large-scale deployment of recovery practices (example of the Harmoni project).

In the context of IS, an example on the use of minerals and chemicals in the pulp and paper sector is provided (Chen, et al., 2015). In particular, Alkylketene dimer (AKD), cationic starch (CS), and polyamide epichlorohydrin (PAE) were used in the modification of precipitated calcium carbonate (PCC), and the use of the modified PCC in papermaking was investigated. It was found that after the PCC was modified, the sizing effectiveness of AKD was enhanced; when PAE was added to the filler, it had better modified effects than when CS was added. When the addition of PCC and AKD were fixed at 20% and 1% (based on the dry weight of PCC), respectively, the retention of PCC increased from 42.5% to 54.6% when modified by 5% CS, and to 56.7% when modified by 2% PAE. The strength properties (tensile indices, burst indices, and tear indices), opacity, and air permeability of the filled paper were strikingly enhanced, while the brightness was slightly negatively influenced by the addition of PAE. The results indicate that the pre-blend modified method is a promising technique for papermaking in that it enhanced the properties of paper. Main outcomes can be listed as follows: 1. In the presence of cationic starch (CS) or polyamide-epichlorohydrin wet-strength agent (PAE), the sizing effectiveness of alkylketene dimer (AKD) was enhanced, and the addition of PAE had better modified effects than when CS was added. 2. The retention rate of precipitated calcium carbonate (PCC) can be enhanced by the addition of CS and PAE. When the addition of PCC and AKD were fixed at 20% and 1%, respectively, the retention of PCC can be increased from 42.5% to 54.6% (modified by 5% CS) and to 56.7% (modified by 2% PAE). 3. The strength properties (tensile indices, burst indices, and tear indices), opacity, and air permeability of the modified, filled paper was strikingly enhanced, but the brightness was negatively influenced slightly by the addition of PAE.

4.5.2 Project on Resource Efficiency EU and no EU co-funded

FineFuture lead by HZDR (June 2019 – May 2022)

Current flotation technologies do not work adequately for fine particles, below 20 µm in size. This is a serious challenge at present limiting the exploitation of deposits and proper recycling of end of life products containing Critical Raw Materials (CRM). This FineFuture project will advance the fundamental understanding of fine particle flotation phenomena, which will lead to the development of ground-breaking technological solutions. This will not only help unlock new CRM deposits but also contribute to increase the resource and energy efficiency of current operations where the fines are lost to tailings. FineFuture will also enable proper reprocessing of old tailings deposits and be technology-transferred to other raw material particle-based processes within the circular economy, thus leading the way in the sustainable use of resources. For the EU industry the ability to float fine particles will be fundamental in securing access to raw materials in the future, yet to date there is no large scale collaborative effort to achieve this. The FineFuture consortium brings together an industry- and user-driven multidisciplinary team with the skills and experience required to tackle the challenging objectives set up for this project. Through a first of its kind research approach, the consortium's combined expertise in science, engineering and industrial practice will allow a robust and knowledge-based development of innovative fine particle flotation technologies.

This project will thus help boosting EU technologies for sustainable raw material processing in Europe and abroad, contributing to energy- and resource-efficient processing in benefit of the future generations. IMA-Europe (Beglium) and Magnesita de Navarras (Spain) are partners in this project with very strong focus on Ressource efficiency and waste flow valorization.

STOICISM - Stoicism (Sustainable Technologies for Calcined Industrial Minerals in Europe, lead by Imerys)

The main objective of STOCISM is to enhance the competitiveness of the European industrial minerals industry by developing cleaner, more energy efficient extraction and processing technologies. STOICISM is an industry-led project with a specific focus on calcined industrial minerals which are presently energy intensive to produce. Most calcining uses the direct combustion of fossil fuels, contributing to carbon emissions. To meet the overall aim, three key calcined industrial minerals have been assessed in the scope of STOICISM: diatomaceous earth; perlite and kaolin. The processes implemented can also then be directly transferable to many other industrial minerals. In global terms, the EU produces one third of the world's production of perlite, 20% of calcined kaolin and 20% of diatomite. Key markets for these minerals are beverage filtration, coatings, plastic, rubber, cosmetics, insulation and construction materials. STOICISM will research, develop and demonstrate a range of new innovative technologies along the industrial minerals value chain. This will include developments in extraction, beneficiation, drying, calcining and waste recycling. In addition the valorization of the Critical raw materials (CRM's notably Rare earth and Lithium were assessed from the historical waste from extraction). STOICISM delivred significant impacts on the sustainability of the EU's industrial minerals industry by decreasing the use of natural resources (both mineral deposits and energy resources) leading to the sustainable production of better and purer products with less waste and lower environmental impact.

HARMONI (Harmonised assessment of regulatory bottlenecks and standardization needs for the process industry) Lead by CIRCE (August 2017 – Oct. 2019)

HARMONI aims at bringing together all the relevant stakeholders of the process industry to jointly identify, analyse and propose solutions to the regulatory bottlenecks and standardization needs that hamper their innovation processes and the market uptake of their results, necessary to move towards a more sustainable and competitive European process industry. In order to achieve HARMONI's overarching goal, the consortium developed and applied a methodology to ensure an effective collaboration of the 8 sectors involved in SPIRE PPP to elaborate the solutions to the common challenges they face due to non-technological barriers, such as regulatory issues or the lack of European Standards when trying to improve their resource efficiency.

In addition, HARMONI project analysed, compared and proposed recommendations to trigger the transferability of technical solutions among and beyond the SPIRE sectors. The methodology will include the utilization of the existing SPIRE Knowledge platform and the creation of another platform to be linked with CEN/CENELEC STAIR WG for the coordination of the project's standardization activities. The project activities will result in an optimized EU regulatory and standardization framework that facilitates and supports innovation in the process industry; a better participation of the SPIRE community in the EU regulatory and procedures, thus providing the most adequate input to the regulatory authorities; an earlier and more active involvement of the SPIRE community in the EU standardization process; and an overall better environment to maximize transferability rates of technologies across SPIRE sectors. HARMONI consortium includes 3 SPIRE sectorial associations (chemicals, cement and equipment), A.SPIRE, 2 RTDs coming from two SPIRE sectors (steel, ceramic), 1 National Standardization body (DIN) and an experienced RTO to coordinate them (CIRCE). In addition, an Advisory Board will involve the other 5 SPIRE sectorial associations and CEN/CENELE. The minerals sector was involved in the validation of the finindings and the uptake of the project recomendations for the Minerals sector.

STYLE (Sustainability Toolkit for easY Life-cycle Evaluation) (H2020….)

STYLE project aim to address the use of sustainability across of the value chain. As stakeholder IMA is invited to attend the meetings for the validation of these tools and/or recommendations. This SPIRE project involved all eight SPIRE sectors and addressed the maturity of sustainability in each sector and the bottlenecks of further uptake. Carmeuse a lime manufacturing company was a partner in the project for the minerals sector and IMA-Europe was one of the stakeholders involved in the project.

LEILAC (Low Emissions Intensity Lime And Cement) Lead by CALIX (Two projects 2016-2024)

The aim of the project is to develop in situ CO2 capture process for lime/dolime and cement manufacturing: LEILAC will pilot the Direct Separation Reactor (DSR) advanced technology that has the potential to capture unavoidable process emissions and enable both Europe's cement and lime industries to reduce emissions by around 60% to 70%. Direct Separation provides a common platform for CCS in both the lime and cement industries. Calix's DSR technology has been used successfully to produce niche "caustic MgO" since 2012, while trapping the plant's process CO2 emissions. The DSR is an in-situ CO2 capture technique that requires no additional chemicals or equipment. LEILAC project innovation consists in the temperature scale up the DSR.

C4U – (Carbon for You) Lead by University College in London (2020-2024)

As part of the European H2020-EU.3.3.2. - Low-cost, low-carbon energy supply, and under the topic, LC-SC3-NZE-5-2019-2020 - Low carbon industrial production using CCUS, the Project Carbon for U has been granted in 2020. The Paris Agreement sets out a global framework to avoid dangerous climate change by limiting global warming to well below 2 °C and pursuing efforts to limit it to 1.5 °C. Without carbon capture, utilisation and storage (CCUS), it is difficult to realise the temperature levels indicated in the Paris Agreement. In the context of the European Energy Union, CCUS is a vital research and development priority to achieve 2050 climate objectives in a cost-effective way. With the focus on the iron and steel industry as part of the CCUS chain, the EU-funded C4U project will work with eight European countries and Mission Innovation countries (Canada, China and the United States) to address all the essential elements required for optimal integration of CO2 capture into the North Sea Port CCUS cluster. The partners in this projects are steel producers (Arcelor Mittal), Lime producer (Carmeuse), and research institutes, Universities and RTO's.

NECAPOGEN 4LIME (NEgative-CAarbon emission POwer GENeration from integrated solid-oxide fuel cell and lime calciner) UK funding for pilot test facility (2018-2020)

The Paris Agreement is the global commitment to limit by 1.5 to 2°C temperature increase above pre-industrial levels. In addition to low carbon processes, there is also a requirement for negative emissions technologies which can remove 7 gigatonnes of CO_2 from the atmosphere. Energy intensive sectors are under pressure to find ways to meet this societal challenge. Origen Power's 'negative emissions technology' supplies natural gas to a solid oxide fuel cell. About half the chemical energy is converted into electricity and the remainder into high-grade heat which is used to thermally decompose limestone ($CaCO_3$) in a calciner to produce) lime (CaO) and carbon dioxide. The system is configured so that all the CO_2 generated is pure, making it cheap and easy to either use or store. The lime that is produced can be used in a range of industrial processes and, in being used, removes carbon dioxide from the air. A bench scale demonstrator has been built by Cranfield University and the UK Government Energy Entrepreneurs fund has awarded a grant to build a 400 kW prototype at the Singleton Birch facilities in UK.

RE-BIOP-CYCLE Recycling Phosphate from communal sewage treatment plants by Bio-P re-dissolution and crystallisation in a fluidised bed reactor. Pilot plant in Germany (2018-2020)

In agriculture, the application of mineral fertilizer becomes necessary as the soil loses its nutrients over time. Among the most important is Phosphor (P), which is mainly recovered from P mines. One common problem using these resources is the increasing contamination with radiogenic Uranium and Cadmium, both of which end up in fertilizer in concentrations that violate national and international regulations. Phosphate rock is classified as a critical raw material based on the Commission assessment.

Therefore, secondary, uncontaminated P-resources like sewage sludge are gaining more and more attention. The Re-BioP-Cycle project aims at recovery of P from activated and excess sludge by optimising the Bio-P process at a sewage treatment plant in Gießen, Germany. The phosphates are recovered without any endocrinic active substances or organic contaminants. In a fluidized bed reactor, the extracted phosphates will react with (dolo-) limestone to calcium phosphate and struvite, which can be readily used as fertilizers in agriculture. With a P recovery rate of > 50%, the Re-BioPCycle project will adhere to the new sewage sludge regulations in Germany from 2025 onwards while providing a sustainable, cross-industry solution for economic recycling and reuse of secondary P. The end-product will allow a controlled agricultural use of P, thus helping to reduce costs and to avoid overfertilization. This lime-based solution will also address the CRM profile and deliver a solution to recover this material from waste flows.

Separation technology - Clariant (Mineral Bentonite & Water)

Year after year, around 800 million tons of water-borne sediments (i.e. accumulations from shipping channels, port basins, mining activities etc.) are processed worldwide. Approximately 30% of this may be polluted with toxins (fertilizers, pesticides and other chemical pollutants and heavy metals). Such sediments may not be used, but nevertheless require costly dewatering, with the associated risk that some contaminants will be released in the filtrate water. Retaining contaminants within the sediment and producing a drier transportable material, while generating a cleaner filtrate can dramatically reduce water treatment and sediment disposal and storage costs. In addition, the mining industry faces a variety of sediment challenges, from surface and underground water-borne sediments to tailings, all of which have unique challenges pertaining to operational efficiency of the mine, the safe handling, storage and recovery of tailings and water, as well as the final rehabilitation of closed mines.

A unique bentonite-based performance dewatering system for the mining, coastal and riverine dredging and tunnelling sectors has been developed to deliver superior technical, cost and environmental performance. Possibility for re-use of sediments as raw materials to eliminate up to 100% of disposal costs. This innovative, high-performance system is an exceptional fit for the dewatering of hard-to-treat and fine sediments in a variety of industrial settings, across the fresh-to-salt-water environmental spectrum, delivering substantial economic, environmental, and sustainability benefits for end users. A much clearer filtrate is achieved that can be returned to nature or more easily reused by the customer, substantially reducing the need for and cost associated with downstream water treatment.

4.5.3 Projects on industrial symbiosis funded by EU and co-funded by non-EU

EPOS – (Enhanced energy and resource Efficiency and Performance in process industry Operations via onsite and cross-sectorial Symbiosis) Lead: University of Gent (2015 – 2019). The EPOS project aims at enabling the implementation of a simple and single management tool for cross-sectorial industrial symbiosis, providing a wide range of technological and organisational options for rendering business and operations more efficient, more cost-effective, more competitive and more sustainable across various process sectors. The sectors involved were: minerals, chemicals, steel, cement, etc.

CORALIS (Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis) Lead by CIRCE (Oct. 2020 – September 2024). To develop an overall framework for the evaluation of the Industrial Symbiosis (IS) readiness level. Three pillars will be assessed extensively: 1. Technological Readiness Level (TRL) scale, 2. Economic Readiness Level (ERL) and 3. Managerial Readiness Level (MRL) in the implementation of an IS solution. 8 sectors** involved in CORALIS. 29 Partners across 8 industry sectors of SPIRE (minerals, chemicals, cement, ceramics, steel, water, non-ferrous metals and engineering) under the leadership of CIRCE (ES). IMA is partner in the project and decicated events for the minerals will assess the sector readiness for the IS uptake.

1. **RECOBA** (Cross -sectoral REAL-TIME SENSING, ADVANCED COntrol and optimization of BAtch processes saving energy and raw materials); 2. REE4EU: integrated high temperature electrolysis (HTE) and Ion Liquid Extraction (ILE) for a strong and independent European Rare Earth Elements Supply Chain where Elkem partner in two projects

RECOBA – Cross-sectorial real-time sensing, advanced control and optimisation of batch processes saving energy and raw materials.

EU-project Spire – REE4EU. Pilot scale set-up and operation of the integrated recycling process of Rare Earth Elements for permanent magnets and Ni-hydrid batteries • Elkem Technology is responsible for the pilot part in REE4EU • The process is an integrated High Temperature Electrolysis and Ion Liquid Extraction.

CSM (CSM, Funding National Finnish Funding Agency for Technology & Innovation (TEKES); 2011–2016) The stepwise carbonation of serpentinite, a rock composed mainly of magnesium silicate mineral serpentine reacts with the CO_2 to form a stable compound, thus fixing the CO_2 permanently. The reaction kinetics have received attention but the work done in Carbon Capture Storage Program (CCSP) is unique in having the minimization of energy input and chemicals use as starting point. <u>Objectives</u>: the CSM project aims at promoting CO_2 fixation by metal oxides into thermodynamically stable carbonates while benefiting of the exothermicity of the carbonation reaction. Application of the mineral carbonation process at an industrial lime kiln was investigated in a pilot plant as part of the CCSP in Finland. <u>Meaningful outcomes</u>: Operating at 80 bar carbonation pressure with ~22%-vol CO_2 flue gas without capture, mineral sequestration may be accomplished at an energy penalty of 0.9 GJ/t CO2 electricity besides 2.6 GJ/tCO2 heat which can be extracted from the kiln gas; Direct mineralisation of flue gas instead of separated and compressed CO_2, eliminates expensive and energy intensive processes to isolate and compress CO_2, resulting in significant lower materials and energy requirements for the overall CCS process chain; An exergy analysis is used to optimise process layout and energy efficiency, and maximise the amount of CO_2 that can be bound to $MgCO_3$ given the amount of waste heat available from the lime kiln; Producing $Mg(OH)_2$ (and Fe,$Ca(OH)_2$) from local rock material; Operating without CO_2 separation makes CSM an attractive and cost-competitive option when compared to conventional CCS involving underground storage of CO_2;

Using serpentinite as a CO_2 capturing mineral looked promising, but replicating to limestone minerals technical difficulties and the results were quite poor.

CO2ncrEAT (CO2ncrEAT, Innovation Fund; 2023-2033) project will support industry in Wallonia to decarbonize, by offering a sustainable solution for the construction sector. Objectives: aims to reuse approximately 20,000 tonnes of CO_2 annually from the lime operations and recovering it as a raw material to produce building blocks. Meaningful outcomes: the concrete result of the project is an eco-responsible block which will make an impact on the decarbonization of the building block and lime industry at the same time.

Mineral LOOP (LOOP, Walloon Region;) Mineral waste are currently very little recycled and mainly put in landfills. Their recycling is currently economically difficult, notably because of the low value of the by-products and the cost of transport. Objectives: Mineral LOOP project aims to design, develop, install, and operate a pilot plant for transforming mineral wastes/by-products into higher value-added products. To achieve this, within the project innovative solutions in mineral waste pre-conditioning techniques, carbonation reaction processes and post-treatment processes will be developed. Meaningful outcomes: A first stage will identify, characterize, and select the potential mineral waste/by-product streams, also evaluating the need and developing pre-conditioning treatments to optimize the carbonation process. Development and optimization of the carbonation processes and post-treatments to meet higher added-value products are also part of this first stage. A second stage will scale-up the results from the previous stage into a first demonstration plant that will process mineral waste/by-product streams and valorize higher added-value products. These products will be used in construction applications. Throughout the project, LCA analyses will validate the options chosen to demonstrate positive results in terms of environmental impact reduction of the processed mineral waste/by-product streams.

4.5.4 Projects related to access of Raw materials

Knowing the enabling role of minerals for so many industrial sectors, the challenge of accessing the raw materials and the framework conditions that condition and regulate the access them in Europe, multiple EU projects were dedicated to address these challenges. Some of these projects are:

Minatura 2020 – addressing the challenge of the definition of Mineral Deposits of Public Interest.

MINLAND – the framework conditions at national / regional level conditions to access these raw materials.

MIREU dedicated to mining regions.

4.6 Water Sector

4.6.1 State of the art of the industrial symbiosis in water sector

The European Environment Agency states that about 44 % of total water abstraction in Europe is used for agriculture, 40 % for industry and energy production (cooling in power plants), and 15 % for public water supply. The main water consumption sectors are irrigation, urban, and manufacturing industry. From the industrial water consumption approximately, half is used as cooling water for energy production while the other half is predominantly used for process and manufacturing industries in chemicals, food and feed, paper and pulp, oil and gas, textile, metals, minerals and mining sectors[2].

As appetite for the world's most important resource continues to grow – from water use in industrial processes and agriculture to intensity of urban demand – a new European consortium called **NextGen** (NextGen, H2020; June 2019-May 2022)is setting out to challenge embedded thinking and practices in the water sector. By embracing 'circular economy' principles and technological innovation to preserve natural capital, optimise resources and improve system efficiency, NextGen aims to boost sustainability and bring new market dynamics throughout the water cycle. Tangible, high-performance innovation, business models and governance conditions to mainstream these solutions are at the heart of NextGen, with 10 large-scale demonstrations in eight different EU countries. Six sites will demonstrate a completely new approach to water supply infrastructures and solutions in urban or rural areas. The circular economy transition to be driven by NextGen encompasses a wide range of water-embedded resources: water itself (reuse at multiple scales supported by nature-based storage, optimal management strategies, advanced treatment technologies, engineered ecosystems and compact/mobile/scalable systems); energy (combined water-energy management, treatment plants as energy factories, water-enabled heat transfer, storage and recovery for allied industries and commercial sectors) and materials (nutrient mining and reuse, manufacturing new products from waste streams, regenerating and repurposing membranes to reduce water reuse costs, and producing activated carbon from sludge to minimise costs of micro-pollutant removal).

In a recent Master Thesis (Bürger, 2019)„Reuse of Treated Wastewater in Industrial Symbiosis", a categorization of the main water consuming applications within industries was established. The main water consuming applications within industries were found to be cooling water, boiler feed, the washing of vehicles and water for recreational purposes. The reuse within agriculture and directly at the wastewater treatment plant were also investigated although mainly through literature. It was found that a large interest in the topic is present within the industries and the environmental incitement is strong.

An interesting industrial initiative is the recent project in Kalundborg with a partnership between 9 public and private companies (http://www.symbiosis.dk/en/), which foresees g**rowing algae on process water from Industrial Symbiosis**. In this project are tested and demonstrated water remediation, production of microalgae biomass and related technologies, on the basis of industrial process water as a resource.

In a recent research, an in-depth review of the literature on IS cases in emerging and frontier market countries was conducted to provide future researches with information on the similarities, weaknesses, strengths, and elements to consider in addressing the topic and closing research gaps in the area (Boom-Cárcamo & Peñabaena-Niebles, 2022). In addition, a mapping was made of the evolution of studies on IS according to country, economic activity, distribution by journal, year of publication, methods used, barriers and drivers in the case studies, and the importance of this topic in the current academic context. In particular the development of IS in emerging and frontier market countries was investigated and, as such, contributes to defining a baseline against which strategies can be designed to move these countries toward the development of cleaner production technologies and environmentally sustainable processes. Results show that IS is a possible environmental planning strategy that can promote

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[2] https://ecwrti.eu/

the circular economy, sustainable development, the improvement of business conditions and the use of waste materials and by-products that were previously considered waste, including wastewater.

Recently, IS has obtained worldwide concern as a new initiative for achieving collaborative benefits through the exchange of resources including water among industries. Even though these initiatives became prominent as successful projects in the early stages, many of them have resulted in failures in the long term due to the absence of the prior evaluation and optimisation of identified water synergies in IS planning. Further, the main attention has been given to achieving cost reductions in individual plants rather than analysing the environmental benefits of IS networks that can be achieved through the maximum recovery of wastewater. In this context, the existing evaluation emphasises the need to have a standardised way to assess the optimum water flow of IS. Thus, the purpose is to conceptualise a model to assess the optimum water flow of IS based on secondary data analysis. In particular, a conceptual model was developed to assess the optimum water flow of IS, which was evaluated through expert interviews to identify further improvements (Mallawaarachchi, Karunasena, Sandanayake, & Liu, 2023). The developed model forms a unique foundation for assessing the optimum water flow of IS, applying in any context subject to context-specific enhancements. Most importantly, the novelty can be highlighted as the consideration given to maximum wastewater recovery in achieving the reduction in the freshwater utilisation of industrial entities within the IS network. Motivated by the limited attention given to water management in IS research, a recent study presents the first global review of water innovation practices in the implemented industrial symbiosis cases reported in literature (Ramin, et al., 2024). The prevalence of global water innovation practices extending beyond the commonly used broad practices of water treatment and reuse to propose six categories, including utility sharing for alternative water supply, utility sharing for wastewater treatment, water recovery, energy recovery from water, material recovery from water, and material exchange to enhance water/wastewater treatment were analysed. Findings highlight regional variations in adoption, with Asian and Europe showcasing diverse practices. Additionally, they indicate that most symbiosis cases center on the extensive role of public utilities and shared water facilities in pursuing water innovation, while 'pure' interfirm water-related symbiosis is limited. Finally, this review highlights extensive knowledge gaps and research needs in advancing sustainable water management and innovation in IS. In particular, the main objective was to extract valuable information on water innovation practices on the existing global IS cases to draft a comprehensive database on water-related practices, including type, distribution and the industrial sectors involved. Particularly, the involvement of municipal wastewater treatment plants in public-private partnerships was assessed, as they play an important role in the identified water-related symbiosis practices. The main achieved result included a comprehensive review of documented IS cases in the literature. 57 cases with water innovation practices were identified. Regional developments in adopting water innovation in IS and the type of water innovation, distribution, and sectoral analysis were analysed, by identifying knowledge gaps in adopting water innovation in IS. Overall, this study contributes to the development of a comprehensive framework for water innovation practices in industrial symbiosis and emphasizes the need for future research in this area.

4.6.2 Project on industrial symbiosis EU and no EU co-funded

A consortium of 26 partners, led by WRE member KWR, was recently awarded funding under Horizon 2020 for a project entitled "indUstry water-utiLiTy symbIosis for a sMarter wATer society" (**ULTIMATE** https://www.kwrwater.nl/projecten/ultimate/).The project aims to become a catalyst of a particular type of industrial symbiosis – henceforth termed "Water Smart Industrial Symbiosis" (WSIS) – in which water/wastewater plays a key role both as a reusable resource per se but also as a vector for energy and materials to be extracted, treated, stored and reused within a dynamic socio-economic and business oriented industrial ecosystem. Symbiosis promises benefits from lower costs as well as new types of revenues, exploiting 'waste' management not only as a legal obligation but as a new business opportunity. The EU has understood this potential but the transition is not easy and requires rethinking and redesign of workflows, processes and business models to create effective, efficient and profitable symbiotic models within industrial sectors and between industry and water service providers. To this effect, ULTIMATE will develop and demonstrate systemic inter-linkages focusing on four of the most important industrial sectors in Europe: the agro-food processing industry, the beverages industry, the heavy chemical/petrochemical industry and biotech industry. Case studies include sites where high-value resources are recovered from industrial wastewater to be used internally or by neighbouring sectors, as well as sites where resources are recovered from municipal wastewater for use by industry.

Water2Return (H2020, Jul 2017-Dec 2020, https://water2return.eu/the-project/) "Resource-oriented solutions for wastewater treatment based on a circular economy approach". Water2REturn constitutes a technological breakthrough conceived to recover and recycle nutrients from slaughterhouse wastewater in the framework of a Circular Economy model. Nutrients recovered are turned into value added products for the agro-chemical industry. At the same time, slaughterhouses solve their wastewater management problems, and reduced costs related to water consumption.

NAIADES (H2020, Jun 2019-May 2022, https://naiades-project.eu/about-the-project) A holistic water ecosystem for digitisation of urban water sector. The project will promote innovative water management solutions to improve services for homes and public buildings, such as shopping malls and hospitals. In particular, NAIADES strives to optimize the market development of integrated and cyber-resilient ICT solutions and systems for smart water management, and opening up of a digital single market for water services. NAIADES aims to leverage the so-called Digital Security strand by focusing on increasing the privacy and the security of ICT – based smart water management systems, through the exploitation of the following NAIADES features:

a) a more user-centric approach to security management. NAIADES will allow users to better control how their data is shared with third parties finding the right balance between privacy and added value;

b) a blockchain-backed logging architecture that provides anti-tamper and early warning protection for critical log and event feeds. NAIADES is going to be a market leader in water sector security by providing a decentralized data protection infrastructure;

c) a Data- driven business innovation.

POWER (H2020, Dec 2015 - Nov 2019, https://www.power-h2020.eu/) "Political and social awareness on water environmental challenges". The Project set up a user-driven Digital Social Platform (DSP) for the expansion and governance of POWER existing water networks. It is a platform for innovation and growth, by engaging on a large scale with stakeholders in the co-creation and delivery of digital products and services to citizens involving awareness-raising, new policy initiatives and deployment. The POWER Water Community model will provide the space to share and exchange knowledge, allowing householders and schools to monitor water use online. This will effectively enhance social interactive mechanisms and increase individual and collective awareness. By connecting citizens through a network on the water platform, they will be able to learn of good practices from other citizens and communities, exchange advice on the best ways to reduce water consumption and collaborate in water efficiency initiatives.

INSPIREWATER (INSPIREWATER, Grant agreement ID: 723702, 2016- 2020) project aims at increasing water and raw material efficiency in the process industry and at implementing sustainable water treatment solutions, through the development, demonstration and exploitation of innovative, eco-efficient technologies supporting sustainable water resources management. Developed technologies will increase water and resource efficiency by 20-30% in the process industry.

The project, focused on the steel and chemical industries, aims at applying the technologies across further process industry sectors for maximum impact. Involving steel and chemical industries, technology and innovation SME's, research organizations and dissemination and exploitation experts, it will deliver quality innovation and striking impact in the process industry.

4.7 Cement Sector

4.7.1 State of the art of the Industrial Symbiosis in the Cement Sector

Cement is one of the primary building materials obtained from limestone, clay and sand. Raw material preparation, clinker production and cement preparation are the main steps of the cement production (Agency, 2009). The most common form of cement is Portland cement, which is based on primary raw materials and commonly associated with combustion of vast amounts of fossil fuels. About 93–97% of Portland cement consists of a material called clinker, which is formed when the raw material limestone burns at a high temperature in a cement kiln (WBCSD/CSI, 2009). The production of clinker, the most energy-intensive step in cement-making, takes place in a kiln where raw materials (limestone, shale or clay, and other materials) are heated up to 1,450 °C; the kiln can be fired by fossil fuels (natural gas, coal) but this is being replaced more and more with alternative fuels (waste derived fuels, tyres, etc.) (SPIRE, 2020).

According to (Hendrik, 2002), the cement industry has a long history of using several wastes as fuels and raw materials, by reducing CO_2 emissions (Battelle, 2002) (Holcim, 2006). In industrial ecology, the cement Industry is defined as "scavenger" (Reijnders, 2007). In addition, the following points were discussed:

1. Study all major streams of material and energy related to cement production.

2. The relationship and integration between the cement production plants and other relevant streams of surrounding industrial and societal systems.

3. All waste materials and energy streams to be viewed as potentially useful internally, or for other industrial processes (Ammenberg, Roozbeh , Helgstrand, Eklund, & Baas, 2011). Aiming

to contribute to a better understanding of the climate performance of different ways of producing cement, and different cement products, this study allowed CEMEX to more systematically and rationally assess different cement sites, and production approaches, from a climate perspective, thereby, making it easier for the company to analyse different options for improvements.

There are also many scientific papers which are focused on the cement industry, dealing with or at least referring to industrial ecology and industrial symbiosis (Ammenberg, 2015) (Feiz, 2013). In (Ammenberg, 2015), there is a study on how relevant the leading ideas of IS are for the cement industry based on a quantitative comparison of the CO_2 emissions from different cement production systems and products, both existing and hypothetical. According to (Haschimoto, 2010) and thanks to the best-known eco-town projects Kawasaki Eco-town, where more than 70 companies are located, a cement producer reduced CO_2 emissions by 43,000 t per year using recycled materials rather than virgin materials.

A recent study elaborates on the link between CE and IS through a case study on a large cement producer in Denmark (Aalborg Portland which is the world's largest producer of white cement) (Ramsheva & Remmen, 2018). The study looks at the potential of reducing CO_2 emissions by the use of alternative fuels and alternative raw materials taken from a variety of waste streams and therewith reducing the recourse to primary fuels and primary raw materials. It aims to demonstrate the mitigation of the environmental impact of cement production through the use of alternative fuels/raw materials and the main results demonstrate synergies with public and private partners to lower resource input costs and improve resource efficiency.

The carbonation of alkaline industrial wastes is a pressing issue that is aimed at reducing CO_2 emissions while promoting CE. In a recent study, the direct aqueous carbonation of steel slag and cement kiln dust in a newly developed pressurized reactor that operated at 15 bar was explored (Biava, et al., 2023). The work aimed at identifying the optimal reaction conditions and the most promising by-products that can be reused in their carbonated form, particularly in the construction industry. A novel, synergistic strategy for managing industrial waste and reducing the use of virgin raw materials among industries located in Lombardy, Italy, specifically Bergamo–Brescia was proposed. Initial findings are highly promising, with argon oxygen decarburization (AOD) slag and black slag (sample 3) producing the best results (70 g CO_2/kg slag and 76 g CO_2/kg slag, respectively) compared with the other samples. Cement kiln dust (CKD) yielded 48 g CO_2/kg CKD. It has been showed that the high concentration of CaO in the waste facilitated carbonation; on the other hand, large amounts of Fe compounds caused the material to be less soluble in water, affecting the homogeneity of the slurry.

4.7.2 Projects on Industrial Symbiosis deeply involving the cement sector.

FISSAC (FISSAC, H2020 WASTE 2014; 1/09/2015 – 29/02/2020) "Fostering Industrial Symbiosis for a Sustainable Resource Intensive Industry across the extended Construction Value Chain" Objectives: To establish a sound valorisation scheme for EAF and LF slag similar to blast furnace slag. The incorporation of EAF and LF slag into cement in a similar manner to BF slag. Developing and demonstrating a new paradigm built on an innovative industrial symbiosis model towards a "zero-waste" approach in the resource intensive industries of the construction value chain, moving to a circular economy. Implementation of the innovative industrial symbiosis model in a feasible scenario of industrial symbiosis synergies between industries and stakeholders. Results: A novel cloud-based platform helps industries minimise waste and enhance sustainability; Valorisation of waste for circular rather than linear processes. Among different materials, LF slag and EAF slag have been used in different case studies: Green concrete slab, Pre-industrial production of CSA cement, Industrial production of Blended cement, Concrete pavement, Autoclaved aerated concrete blocks (Building wall), Precast Concrete Elements (Pavement and New Jersey). Putting information and resources in the hands of decision-makers. Enhancing industrial symbiosis across sectors throughout Europe.

4.8 Ceramics Sector

4.8.1 State of the art of Industrial Symbiosis in the Ceramics Sector

The European ceramic industry is composed of world-leading companies and SMEs that manufacture value-added solutions by transforming mineral raw materials into sustainable and innovative products (Cerame-Unie, Cerame-Unie, Facts & Figures, s.d.).

Thanks to its features, ceramic is an extremely durable material with an estimated lifetime of more than 50 years and is easy to recycle/recover in processes that reuse fired and unfired waste and demolition waste according to the CE perspective (Ceramica, 2019).

The European ceramic industry is structured in nine sectors ranging from construction products and consumer goods to industrial processes and cutting-edge technologies (Cerame-Unie, Cerame-Unie, Facts & Figures, s.d.). According to European data, its production is around 1304 million m^2, consumption amounts to 964 million m^2 and total sales were close to about € 9 billion in 2016 (Baraldi, 217).

The most important ceramic subsector is the floor and wall ceramic tiles and the most common ones are earthenware tiles, glazed stoneware tiles and porcelain stoneware tiles (ASCER, s.d.). Spain and Italy are the largest producers accounting for around 80-90% of the total European production (Baraldi, 217).

The ceramic industry is by definition an energy intensive one mainly based on combustion processes and, therefore, subject to European policies aiming at reducing greenhouse gas emissions. Not only a high amount of energy is consumed during the production process, but also the energy cost is a significant percentage of the total production costs (Christos Agrafiotis, 2001). In 2011, “Roadmap for moving to a competitive low-carbon economy in 2050” has been published by the European Commission and, for the industrial sectors, the objective is to reduce CO_2 emissions from 83% to 87% by 2050 (Commission, A Roadmap for Moving to a Competitive Low Carbon Economy in 2050 , November 09, 2017). Therefore, in 2012 the European Ceramic Industry published “Paving the way to 2050- The Ceramic Industry Roadmap” which considers alternative energy sources and current and future production of technologies in order to consider the complete lifecycle of ceramics (Cerame-Unie, Paving the way to 2050, the ceramic industry roadmap, 2012).

With its wide range of applications, from construction to consumer goods, industrial processes and cutting-edge technologies, the ceramic industry is consistently developing innovative and high-value solutions (source: http://cerameunie.eu/). This sector continues to develop, attempting to reduce costs, improve the reproducibility of products and compete with other markets' products by developing new equipment and having better knowledge of ceramic properties and evolution (Marisa Isabel Almeida, 2016).

The ceramic sector is committed to reducing CO_2 emissions and wastewater and to recovering and recycling its materials whenever possible (Cerame-Unie, Paving the way to 2050, the ceramic industry roadmap, 2012). Most of the production residues (unfired waste tiles, fired waste tiles, washing line sludge, polishing and honing sludge, dried milling residues and exhausted lime) can be used and reintroduced into the ceramic production process in place of other raw materials. The extraction, transport and use of thousands of tonnes of materials of natural origin such as sands, feldspars, alumina, zirconium oxide, mullite and clays can therefore be avoided (Ceramica, 2019).

In Italy 99.5% of the sector's production and purification waste is reused in the production cycle, making up 8.5% of the mineral raw material requirements of the manufacturing process and in 2015, 70% of the required water in the Italian ceramic industry was recycled wastewater (SPIRE, 2020). Thanks to Resolution no. 16604 of 23/10/2017 associated with the Regional Law on the Circular Economy, the Emilia-Romagna (Italy), regional government recognised four by-products originating from the ceramic sector that can be used effectively within the ceramic production process:

- unfired ceramic powders and bodies;
- powders from fired ceramics;
- unfired formed ceramic products (whole or fragments);
- fired formed ceramic products (whole or fragments).

For this objective, some industries of the “Zona Industriale Prataroni”, a ceramic industrial district located in Civita Castellana in Emilia Romagna (Italy), joint the APEA ZICC (Zona Industriale Civita Castellana) to adopt a circular economy approach created by an industrial symbiosis, by means of both circular and green economy-based applications. All the involved companies gave to the partnership their wastes, plants and knowhow available in order to produce water for ceramics manufacturing and thermic and electric energy for self-consume (Carlini, 2019).

In the context of the transition from a linear “produce, use, waste” model to a circular model where resources and materials are reused, recycled or recovered is a high priority topic on the EU political agenda of the ceramic sector, according to the new Circular Economy Action Plan by the European Commission. In this transition the Ceramic Industry contributes to the shift towards CE by innovative production processes and sustainable products (Cerame-Unie, Circular Economy & Sustainability, 2021). Nevertheless, it is important to underline that the chemical transformation of clay to ceramics does not allow for a 100% closed loop recycling. In the context of resource efficiency, it is important “using less” and, at the same time, “using better”. Ceramic products are resource efficient and stand out with their high durability thanks to their long lifespan. After the end-of-life stage, ceramic products can be reused, recycled, or recovered. In this regard, the ceramic sector has developed innovative solutions in order to reduce the raw material consumption and waste generation during the production process. In addition, through the reuse of waste from other industrial processes, according to the concept of IS, an optimised raw material selection and product design, and supply chain cooperation are already in place.

G3NIUS is the new line of eco-friendly products supported by the European Commission through the LIFE programme. It has been designed and engineered with the environmental performance of the product throughout its entire life cycle from cradle to grave, by digitizing production processes in line with the Industry 4.0 manufacturing paradigm (GRESMALT, G3NIUS-ENVIRONMENTAL PRODUCT DECLARATION). A network of line sensors assesses technology and sustainability KPIs in real time during G3NIUS Industry 4.0-based production. This product minimizes its environmental impact throughout its entire life cycle, reducing the use of non-renewable resources and reusing processing waste and secondary raw materials

(SRMs), by maintaining the quality and utility function of the ceramic building product, which is also enhanced by its inherent durability (50 years). In particular, this cradle-to-grave approach includes a detailed assessment of the carbon footprint of the product beyond the boundaries of manufacturing plants, using the Life Cycle Assessment (LCA) tool, which follows the standards of ISO 14025:2010 and EN 15804+A2:2019. In this context, the Total Carbon Footprint of Products of ceramic tiles produced by G3NIUS technology, calculated using primary data for the manufacturing and electricity procurement phases, and estimated through scenario analysis for the sourcing phase, was: 7.46 kg CO_2-eq/m^2 (GRESMALT).

4.8.2 Projects on Industrial Symbiosis deeply involving the ceramics sector.

INSYSME (INSYSME, 2013-2016) project aims at developing innovative systems for masonry enclosures, to be used for façades, envelopes and internal partitions of reinforced concrete framed buildings, to derive sound concepts for their analysis and to develop reliable, simple and efficient methods for their design in the everyday engineering practice. Masonry enclosure systems have excellent, yet still improvable, performance with respect to healthy indoor environment, temperature, noise, moisture, fire and durability. However, they have been considered for long time as non-load-bearing, non-structural elements. In reality, they can play a structural role in the overall seismic behaviour of buildings. Enclosure walls need to be checked against excessive damage and potential out-of-plane collapse. Under this respect, as proven by recent earthquakes, if they are not properly detailed to accommodate seismic loads and correctly designed, they represent a significant hazard and can result in extensive economic losses as well as in a source of danger for human lives. Hence, it is necessary to reconsider the structural role of enclosures, in order to establish reliable analysis and design procedures and to provide background for an update of current structural codes. Objectives: The adopted approach started from material and technology development. Technical and economic feasibility of the envisaged construction systems were demonstrated by performing parallel experimental and theoretical studies and were validated by prototypes construction. Experimental and numerical characterization aimed at deriving structural requirements of masonry infill walls, as well as tools and methods for their assessment. The research will offer innovative solutions to scientific and technological problems which have a broad-spectrum impact. The experience of SME associations involved in the project, with the aid of all the partners, will ensure that the needs of large communities of SMEs are met.

EUCERMAT (EUCERMAT, 2015-2018) project is co-funded by the Erasmus+ programme. The project aimed at changing the image of ceramics in Europe. The development and implementation of innovative practices to promote ceramic sciences to the community, civil society, high school students and teachers, parents, educators in general, ceramic industry staff, is thus a huge issue. Objectives: The activities of the project aimed to create a new methodology based on a relevant functioning of the knowledge triangle in the domain of ceramic material. Thus, the joint work of the partnership was seeking to create a common space where the interaction between research, education and innovation is optimized. To achieve these objectives the project was setting up various activities closely connected. Meaningful Outcomes: The joint work of the partnership was seeking to create a common space where the interaction between research, education and innovation is optimised. To achieve these objectives the project implemented various activities closely connected and established “intellectual outputs” in order to help other institutions willing to implement similar activities.

SILIFE (SILIFE, LIFE14 ENV/ES/00023, 2015-2019) “PRODUCTION OF QUARTZ POWDERS WITH REDUCED CRYSTALLINE SILICA TOXICITY”. Prolonged inhalation of crystalline silica particles can cause lung inflammation and the lung disease known as silicosis. It is used in many manufacturing industries such as the cement, ceramics, steel, glass, mineral wool, aggregates, mortar and concrete sectors. Although it is not possible to substitute crystalline silica in many of the sectors where it is used, it is possible to nullify its toxicity by treating it with certain substances. Objectives: The main objective of the SILIFE project is to produce commercial quartz powders that have very little or zero RCS toxicity. This new coating technology would be replicable in any industry that uses separate dry quartz powders as raw materials. Specifically, the project aims to design a pilot plant for the treatment of commercial quartz powders that has the capacity to treat 500 000 kg of quartz per year and demonstrate that the treated powders exhibit much less toxicity than the untreated quartz. Meaningful outcomes: Numerous studies suggest that the toxicity of quartz is conditioned by the surface chemistry of the quartz particles and, in particular, by the density and abundance of silanol groups. The effectiveness of the addition of substances like nano-alumina, aluminium lactate, and organosilanes to block these groups has been studied in the SILICOAT project, showing that the toxicity of the RCS contained in the wet-processed raw materials of the traditional ceramic industries can be virtually nullified. This effect was obtained by adding an additive to the ceramic compositions, which coats the quartz surface so that it becomes no longer toxic. This technology was found to be technically and economically feasible for traditional ceramics.

ECOFILLINK (ECOFILLINK, European Regional Development Fund; 2020-2021). Waste from plastic containers contaminated with ink-jet inks currently amounts to 500 t per year and a volume of 10,650 m3. Recycling these containers is a problem due to their complexity and the dirt released on contact with water, since 5% of the ink remains adhered to the container internal walls, representing losses of 3.6 million euros per year. ITC-AICE and AIMPLAS are aware of the importance of designing a new plastic container for storage and transport of inkjet inks that minimizes its environmental impact through the implementation of different circular design strategies for containers and waste management in line with the circular economy to ensure that resources remain in the economy as long as possible. Objectives: The aim of the project is to reduce the environmental impact generated by ink containers used for digital decoration of ceramic tiles. The EcoFILLink project also aims to implement environmental improvements in packaging design and waste management processes in accordance with the CE.

LightCoce (LightCoce, H2020; 2019-2023). “Building an Ecosystem for the up-scaling of lightweight multifunctional concrete and ceramic materials and structures”. Easy to transport, handle and install, lightweight components are being increasingly used in construction and infrastructure sectors, as well as in the aerospace, automotive and defense industries. Concrete and ceramics are the focus of interest due to their wide range of applications and durability. But their lightweight attributes need to be coupled with enhanced properties and multifunctionalities. The EU-funded LightCoce project will build an ecosystem for the upscaling of these materials and structures. To do this, it will provide open access to SMEs or industry to a single entry point ecosystem that will cover a range of end applications from construction materials (bricks, ceramic tiles) and infrastructures (ready mix concrete and prefabricated components) to high-tech applications in the automotive and aerospace industries. Objectives: the main objective of the LightCoce project is to cover the gap in the upscaling and testing of multifunctional lightweight concrete and ceramic materials by providing open access to SMEs or Industry to a single entry point ecosystem consisting of already developed Pilot Lines including three clusters of existing pilot lines; a. Concrete group, b. Conventional Ceramics group, and c. Advanced Ceramics group, process and materials modelling, Characterization, Standardisation, Regulatory, Safety & Environmental Assessment, Data Management and Innovation Management that will be accessible to the interested stakeholders at fair conditions and cost. Meaningful outcomes: the ecosystem will support the upscaling activities of European SMEs and industry, covering a large range of end applications from constructions materials (bricks, ceramic tiles), infrastructures (ready mix concrete, prefabricated components), to high tech applications in automotive & aerospace industry.

METABUILDING (METABUILDING, H2020; 2020-2023). The METABUILDING innovation ecosystem brings together stakeholders from construction and 4 emerging industrial sectors; recycling & circularity, additive manufacturing, nature-based solutions and digital industry. Objectives: the METABUILDING Platform aims to facilitate collaboration between new partners and experienced experts to further innovation. Meaningful outcomes: the METABUILDING platform is the digital backbone. The METABUILDING platform consists of several digital tools and services that help SME's and other stakeholders engage in successful innovation. In this platform you will find services and information that will assist you in finding existing innovative technologies ready to deployed or project partners seeking collaboration on new exciting projects.

LIFE toSHELLENCE (EGGSHELLENCE, Life+; 2020-2024): A potential raw material for ceramic wall tiles. The project involves two very different production sectors: egg production and processing and ceramic production. Both sectors have established an industrial symbiosis in accordance with the principles of the CE, in this case, reusing the waste of thousands of tons of eggshells produced each year to process them as raw material in the ceramic tiles manufacturing. Objectives: the need to protect virgin and nonrenewable raw materials, together with the previous experience of the members of this project in the field of ceramic processing and waste recovery, has encouraged the consortium to try to demonstrate the technical feasibility of using eggshells as a secondary raw material in the production of ceramic tiles. Meaningful outcomes: this project will result in economic benefits, both for the egg processing industry and for the ceramic industry, but also in environmental benefits, since it will contribute to the implementation of the Waste Framework Directive (Directive 2008/98/EC) following the objectives and targets of the Roadmap for a Resource Efficient Europe.

RECONMATIC (RECONMATIC, Horizon Europe; 2022-2026) “Automated solutions for sustainable and circular construction and demolition waste management”. A suite of innovative tools, solutions and techniques to build bridges through "bottom-up" construction and demolition waste (CDW) prevention and handling to reach "top-down" European waste reduction goals is proposed. The project's agenda reflects the HORIZON-CL4-2021- TWINTRANSITION- 01-11 call objectives, with a focus on integrated decision making that would allow considering all aspects of CDW generation and involving all stakeholders within the construction industry. Current practices in CDW management, from prevention and minimization of waste to its reuse, will be evaluated and markets to support the supply chains and circular economies will be identified. Consequently, a digital information management system for stakeholders' collaboration and waste traceability will be developed, tested and demonstrated. Objectives: it is envisaged that the CDW minimization will be achieved by empowering BIM and integrating waste management relevant data into the information models. Processes of converting different formats of construction information to the digital twins will be automated, as well as the decision-making system for repurposing, deconstruction and demolition. Meaningful outcomes: Automation will be employed for AIassisted CDW classification and robotic segregation off-site. The methodology for CDW logistics in regard to the automatic and more efficient CDW sorting and distribution will be proposed, along with methodologies to provide new added value uses to CDW. The consortium involves 7 research institutions, 10 small to medium enterprises, 5 large companies and 1 association, representing 5 EU countries, UK and China. The feasibility and efficiency of the developed solutions AIM HORIZON EUROPE 28 will be evaluated using 6 demonstrators. This consortium composition will enable us to tackle the whole life-cycle CDW management, propose beyond the state-of-the-art technologies, and contribute to reaching the zero-waste construction industry in Europe in the near future.

2B CONNECT (CONNECT, Interreg Vlaanderen-Nederland; 2019-2020). Objectives: The objective of 2B Connect is to increase biodiversity in the border region BE-NL through close cooperation with companies. We focus on two tracks: on the one hand the greening of companies and sites and on the other hand the internalisation of the theme of biodiversity in environmental management. Greening industrial estates is the heart of the project. In the border region of Flanders-Netherlands, ten areas were selected where we work on biodiversity together with companies. From existing business parks that are being given a biodiverse makeover to new business parks to be developed, where the natural values in the neighborhood are considered during construction. From complete industrial estates to individual industrial lots.

Communication: we draw attention to this theme and inspire companies to work on biodiversity via a promotional website, networking moments with the business world and the green sector, green safaris, a film and much more.

Developing and refining instruments: we develop a calculation application and investigate the costs and benefits of investing in a green business site. We aim to internalize the theme of biodiversity in company policy. We examine which instruments are needed to help companies work on a biodiverse business site.

The biodiversity task force: we train advisors who will also motivate, inspire and guide companies after 2B Connect in increasing biodiversity, both on the company site and in the environmental management systems.

REWACER (REWACER, Valencian Innovation; 2019-2020) is an initiative that contributes its experience and knowledge obtained in carrying out numerous projects related to the field of water in the ceramic sector. REWACER is funded by the Valencian Innovation Agency (AVI), and as a priority, it is going to carry out a critical study for the implementation of a circular water economy model in the province of Castellón, which will help acquire the appropriate knowledge to develop a new business/service model in the efficient management of water in the province, and that, at the same time, promotes the recovery of treated water from its regeneration and therefore its reuse. Objectives: The Institute of Ceramic Technology (ITC) collaborate with the company Estudio Cerámico, SL, the Technological Institute of Energy (ITE) and the firm SAMCA, who define this action as: "an innovative proposal aimed at creating a new water reuse service in the province of Castellón whose fundamental objective is to promote a circular economy of water". Meaningful outcomes: this new water service will consist of supplying the water demand of the ceramic industrial sector with the secondary effluent from the WWTPs (Urban Wastewater Treatment Plants) located in the province of Castellón, thus avoiding part of the discharge of treated water to other channels or to the sea.

SOST-RCD (SOST-RCD, Valencian Innovation Agency; 24 months). The SOST-RCD project, which is funded by the Valencian Innovation Agency (AVI), is aligned with the principles of the circular economy and aims to convert waste materials from construction and demolition into new resources (RCD), thus advancing towards a more sustainable building. SOST-RCD is coordinated by La Torreta Quarry, which is part of Origen, the materials division of Simetría Grupo, and was created with a main scientific and technological objective, focused on the research and development of new technologies aimed at generating products from of RCD. Objectives: the main characteristic of these new products is that they have the same characteristics as construction materials made from virgin raw materials. At the same time, they help improve the current management systems for this type of waste that would normally end up in landfills, proposing and showing the economic and environmental advantages offered by this type of recovered and therefore more sustainable materials. In short, SOST-RCD implies a significant impact on the value chain of the construction sector, in addition to promoting the circular economy as a business model in the productive system of the Valencian Community. With this, a new market is opened by incorporating innovative techniques that are still practically unknown in the sector, which involve new designs of processes, treatments and use of waste to give a new life to another type of construction and building that results in the well-being of those who inhabit the spaces and in the implementation of new economic models aligned with the Sustainable Development Goals. Meaningful outcomes: The project is broken down into three activities. In the first of them, the starting points of the project have been established with regard to the state of the art of the production techniques of current materials, the characterization of the input RCD and the establishment of the global situation of the RCD, both in its generation and in its treatment. The second activity focuses on laboratory-scale work to valorise RCD in different applications: aggregates for concrete and mortar, baked clay products and alkaline-activated products, colloquially known as geopolymers. Finally, in the third activity, pilot-scale tests will be carried out to obtain the different materials under study, carrying out quality controls to validate these applications.

VALUES (VALUES, Valencian Innovation Agency & European Union through the Operational Program of the European Regional Devel-opment Fund (ERDF) of the Valencian Community; 2014-2020) proposes an innovative comprehensive process to recover calcium carbonate from the sludge generated in the paper industry, currently taken to landfills, and use it as a resource in the manufacture of ceramic materials and rubber for footwear, thus reducing energy use, the footprint of carbon and the impact on virgin raw materials. Objectives: Sectors such as paper, ceramics and rubber, thanks to the recovery of calcium carbonate obtained from sludge residues from the paper industry. The calcium carbonate obtained may be used as a secondary raw material, replacing natural calcium carbonate, for which processes that use intensive energy consumption are used and it is that the high consumption of water by the paper industry leads to the generation of large volumes of wastewater which, once treated, generate, large amounts of sludge, an inevitable residue of that treatment. Paper industry sludge is made up of organic matter and mineral fillers such as kaolin and, mainly, calcium carbonate. Meaningful outcomes: proper processing of these sludges will allow the combustion of organic matter, leaving as a residue a calcium carbonate of adequate purity and fineness that can become an alternative source of virgin calcium carbonate, used in various industrial sectors, such as polymers, rubber, paper, etc. Regarding the ceramic industry, the application of the circular economy concept to the paper, rubber and ceramic sectors would allow the transformation of a waste that today goes to landfills, towards obtaining a new resource, which would reduce the consumption of virgin raw materials, as well as the impact on natural reserves of limestone, a non-renewable natural source of calcium carbonate.

EROS (EROS, Ministry of Science, Innovation and Universities – Spain; 2020-2022)**.** The main objective of EROS is to implement a real circular economy system based on the recycling of wind blades and waste from the aeronautical sector to be transformed and used in other sectors such as the ceramic industry, specifically in the ceramic tile supports themselves, and the elements that make up their surfaces, such as glazes, ceramic frits and inks for decoration. This waste will also be transformed, applying the CE principles, to be reused as resources in the transport sector. Objectives: EROS aims, in this way, to reduce the consumption of fossil resources while maintaining long-term sustainability in the supply chain, and also eliminates the negative impact that these materials leave on the environment at the end of their useful life. Meaningful outcomes: The work of ITC consists of collaborating with companies in the sector in the following tasks: Define the requirements of the recycled materials to be introduced in the ceramic tile manufacturing process (supports, glazes, frits, etc.) and subsequent characterization; Develop and characterize new sustainable ceramic materials; Establish a methodology for manufacturing ceramic tiles using fiberglass as flux; Manufacture of demonstrators to validate the solutions developed.

FORTURE (FORTURE, LIFE16 ENV/IT/000307; 2017-2021) project aimed to integrate the three pillars of sustainability (environment, economy and society) into the company's business model. Thanks to digital technologies of Industry 4.0, the tools of environmental (LCA: Life Cycle Assessment), economic (LCC: Life Cycle Costing) and social (S-LCA: Life Cycle Assessment) impact assessments have been transformed from static (based on the analysis of time series) to dynamic (based on data collected in real time). The dynamic model was therefore suitable both to monitor the impacts at the same time in which they are produced, and to implement the approach of eco-design in the evaluation of alternative solutions of processes and products, minimizing the environmental, social and economic impact. Objectives: LIFE Forture has developed and successfully tested a tool for the assessment of environmental and socio-economic impact in real time, along the entire life cycle of the ceramic product. This tool, called DYCTA (DYnamIC susTainability Assessment), has also allowed eco-designing a new collection of tiles with lower environmental impact than the current production that has been launched to the market with the new brand G3NIUS (Eco-friendly Tiles: Smarter. Greener. Better). Meaningful outcomes: Forture project has led to the creation and introduction of a new brand that identifies an innovative technology to produce sustainable ceramic tiles: G3NIUS. The new products were achieved by demonstrating the feasibility of dynamically monitoring the environmental, economic, and social impacts of a ceramic company by integrating sustainability considerations into its enterprise resource planning (ERP) system. This was also achieved by developing a new model for dynamic sustainability assessment (DYCTA).

REDiRECT (REDiRECT, Italian Ministry of Enterprises and Made in Italy (MIMIT); 01/10/2020-30/09/2023) Objectives: combining the principles of circular economy with the digital technologies of Industry 4.0 by developing a new manufacturing model for the ceramic and mining industry called Circular Enterprise 4.0. This industrial model will have to fulfill a triple purpose: 1. be sustainable, both environmentally and socio-economically; 2. be technologically feasible in an operational environment; 3. promote the competitiveness of companies by increasing profitability and profits. Meaningful outcomes: the transition to Circular Enterprise 4.0 will be monitored using the tools of environmental, economic, social, and technological impact assessment based on the perspective of the life cycle (Life Cycle Thinking) and considering the ceramic chain from the extraction of raw materials to the distribution and use of the finished product. In this context, digitization of processes solved the difficulties in implementing the life cycle approach (cradle-to-grave). In addition impact assessments (environmental, social, economic, and technological) using secondary data extracted from general databases and not specific to the sector analyzed were carried out. With Circular Enterprise 4.0, the life-cycle approach will be effective as companies will safely exchange both material resources and information and knowledge, using an IS approach in a context of mutual trust.

START (START, Ministry of Enterprises and Made in Italy (MIMIT); 01/05/2023-30/04/2026) is an Industrial Research and Experimental Development Project on the ceramic industry, which has already successfully digitized its processes within the framework of the Industry 4.0 model. Objectives: START aims to research and validate technological solutions and operational models for guiding the digital transformation of an industrial company up to the scale of product implementation. This will provide valuable data for a continuous process of optimizing the product at an industrial scale. Meaningful outcomes: different actions will be implemented:

- Utilizing artificial intelligence (AI) to enhance operational efficiency in the factory.
- Leveraging hyper-automation to achieve higher quality outputs and outcomes.
- Adopting eco-efficiency criteria guided by AI to meet the demand for more sustainable products.
- Using AI to optimize the use of energy and natural resources.
- Building an agile production environment that surpasses operational standardization.
- Leveraging production agility to provide customers with personalized products.
- Utilizing operational agility to enhance industrial organization resilience and competitiveness.
- Implementing robust cybersecurity systems.
- Optimizing ceramic products as "smart materials" to increase versatility and align with a "Design Thinking" approach.
- Employing an on-site monitoring system to optimize the behavior of building envelopes and improve indoor comfort for occupants.

The digital transformation, transitioning from Industry 4.0 to the Intelligent Industry, will rely on digital technologies, integrating IoT, Big Data, and AI for analyzing and monitoring production processes, technical performance, and sustainability of the organization and its products.

4.9 Waste Treatment Sector

4.9.1 State of the art of industrial symbiosis in the WEEE and batteries sector

Waste of Electrical and Electronic Equipment (WEEE) is the term used to denote a variety of end-of-life equipment coming from obsolete electrical appliances and electric goods (Kaya, 2016).

Metals contribute to the 60% of the equipment weight (Widmer et al, 2005).

The major fraction of metals is concentrated in WEEE specific components, namely the printed circuit boards (PCBs), that besides copper, lead and tin solders contain also precious metals (Ghosh et al, 2015). Some products comprising phosphors, as fluorescent lamps, neodymium-iron-boron (NdFeB) magnets and nickel-metal hybrid (NiMH) batteries contain Rare Earth Elements (REE), which are the lanthanides group elements plus Scandium and Yttrium.

The REE are classified by the European Commission as the most critical raw materials for their high economic importance and shortage production. (European Commission, 2010) and (European Commission 2. , 2014).

A second source of valuable metals is batteries. Especially lithium-ion batteries are of growing interest.

Since their commercialisation, in the early 1990, lithium-ion batteries represented an important energy storage technology (because of their high energy density), which enabled a rapid development of portable electronics such as mobile phones, laptops and tablets. In the last 10-15 years lithium-ion technology strongly entered in transport sector, with application for electric and hybrid cars, buses, trucks and many energy storage systems.

Consequently, the requirement for recycling of lithium-ion batteries increased, although the recycling of lithium-ion batteries is still considered insufficient. In 2019, on a total of 1.25 Mt of lithium battery placed on the global market, the recycled fraction is less than 10% (CEPS, 2018).

The lithium-ion battery value chain can be divided into six key steps: 1) mining and processing of the raw materials; 2) cell components manufacturing; 3) Cell manufacturing; 4) Battery pack manufacturing; 5) installation in electrical vehicle; 6) recycling (CEPS, 2018). Between 5 and 6 steps there is the possibility to re-use lithium battery for a different application.

Lithium battery contains other valuable metals, which are considered critical raw materials for EU by the European commission. Hence the increase of the recycling is mandatory to reduce energy consumption as well as to relieve the shortage of rare resources and eliminate the pollution of hazardous components.

4.9.2 Management and recycling of materials from WEEE

WEEE is one the fastest growing waste streams in the EU and The EU is reliant on imports for many of the raw materials present in WEEE and aims to realise a Circular Economy. Then WEEE must be seen as a source of valuable materials to be exploited. Nevertheless, WEEE is scarcely recycled.

According to the WEEE forum, the International Association of Electronic Waste Producer Responsibility Organisations (https://weee-forum.org/) in 2019 only 17,4% of global e-waste was collected and properly recycled. This correspond to more than 40 million tonnes of e-waste generated globally in 2019, which are either placed in landfill, burned or illegally traded.

This results in the huge loss of valuable and critical raw materials from the supply chain and causes serious health, environmental and societal issues through illegal shipments of waste to developing countries.

Even in the EU, where e-waste recycling is at highest level in the world, supported by a good legislation, only 35% of e-waste is officially reported as collected and recycled (WEEE Forum, 2019).

The WEEE is perfect for implementation of an industrial symbiosis model.

However, securing responsible sourcing of those materials and increasing recycling rates is a complex societal challenge, for several reasons, including lack of structured data on the quantities, concentrations, trends and final whereabouts in different waste flows of these secondary raw materials in the Urban Mine in Europe, availability of efficient technological solutions for selecting and recovering materials (PROSUM, 2017).

The adoption of more sustainable and cooperative strategies (such as reuse and remanufacture) is driven by policy and legislative requirements, which create a favourable environment for the development of industrial symbiosis models in the e-waste sector. However, only few practical implementations can be found in the market (Marconi, 2018).

From a technological point of view, the current technologies are not efficient; they consume a high quantity of energy and release emissions to air and water. The existing recycling industry for the recovery of metals from WEEE is still at low mature stage. Base metals (such as aluminium, copper, etc) and precious metals are extracted and recycled in significant amount; on the contrary Rare Earth Elements (REE) are practically almost never recycled. Moreover, the existing technologies for WEEE recycling are mainly based on smelting processes and or hydrometallurgical treatments, which have significant impact on the environment because of the generation of secondary pollutants. The development of environmentally friendly and cost-effective treatments is strongly required. The WEE recycling chain includes three main steps: (i) collection, (ii) pre-treatments, (iii) end-refining processing (Marra A., 2018).

The collection of WEEE, which determines the amount of materials entering the recovery process, strongly depends on the consumer awareness, in order to make the electronic waste available for recycling, as well as on logistic and organization, which must facilitate the collection.

Pre-treatment is an essential step, and must be improved in order to reduce the costs and to increase the efficiency of the yield of the valuable materials.

After collection and dismantling , WEEE are subjected to a manual sorting to separate hazardous substances, useless parts and components holding valuable materials. Then, the waste is processed through mechanical treatments, namely size reduction and physical separation processes

The techniques employed for WEEE mechanical treatments have been transferred from the mineral sector. Shredding, screening, magnetic separation, eddy current separation, corona electrostatic separation and density-based separation can be found in a conventional WEEE mechanical treatment line.

Mechanical processes are well designed to recover mass relevant metals, as iron and copper, with yields up to 80% whereas they fail in the recovery of precious metals which are often lost in the dust streams (Marra A., 2018).

In the end-refining processing, non-metallic fractions resulting from the mechanical separation processes, can be treated through processes as gasification, pyrolysis, supercritical fluid depolymerization and hydrogenolytic degradation with the main aim of producing chemical substances and fuels. Metallic fractions are sent to further recovery via techniques coming from the metallurgical sector, such as pyrometallurgy and hydrometallurgy. End-refining processes require special technologies.

Today, electrometallurgical processes, including electrowinning and electrorefining, are generally applied at the end of the recycling chain. These processes are based on the electrodeposition of metal concentrates in aqueous electrolytes or molten salts. In the last years biometallurgy has attracted great attention as promising technique for the recovery of metals from WEEE at lower costs and minor environmental impacts compared to the conventional treatments. Emerging technologies in the field of electrochemistry, supercritical fluids, mechanochemistry and ionic liquids are being explored (Marra A., 2018)..

The scientific and industrial research is currently directed towards the optimization of these processes in order to ensure the recovery of precious metals as well as REEs whose fate has not been addressed yet (Marra A., 2018).

Although the benefits of WEEE recycling are well-recognized, the effective recovery of materials from electronic waste is still challenged by technical, environmental, economic, social and cultural aspects.

Some necessary lines of development have been individuated (Marra A., 2018).

- The WEEE are complex and heterogeneous, difficult to treat in recycling processes. Improvement can come from an eco-design approach, where the electric and electronic devices are designed, not only in view of the performance in service, but also for a easier recycling.
- Large amount of valuable materials is lost through the entire recycling chain owing to a poor waste collection and inadequate technical capacities of recycling infrastructures. Improvement can come from new advanced technologies, more efficient and at lower environmental impact, for sorting, treating and recovering metals. The aim is to increase the yield and to extent the recycling to more metals
- To improve the recycling it is also necessary the awareness of the consumers and the development of infrastructures for collecting and treating the WEEE in a more adequate way, enlarging the focus to the valuable metals, such as REE, substantially neglected today.
- For pursuing and promoting good recycling practices, virtuous cooperation and coordination among the stakeholders involved into the WEEE management system are fundamental as well as the role of regulations and policies, for limiting the amount of WEEE exiting from the legal and organized cycles.

4.9.3 European projects in WEEE sector

Lithium batteries are complex system, hence dismantling and separation of components require much more attention, work and, consequently, cost, than in most of WEEE. In general, preliminary retreatment before recovery of the valuable metals from the waste is necessary (Xianlai Zeng, 2014) (CEPS, 2018)

It is worth to mention that lithium batteries are also re-used for different application, with less stringent requirement than the original ones. For example, big batteries. dismantled from transport systems. can be re-used as backup power in homes or telecom power.

The higher complexity does not prevent the lithium battery recycling, as often reported, but not true (CES, 2019). However, the recycling methods and the organisation of the recycling differ in different market and geographical areas.

In Europe there are about ten companies that treat lithium-ion batteries (CES, 2019) and Europe is among the market leaders for the recycling of lithium-ion batteries (CEPS, 2018). However, the battery recycling industry is not yet adequately developed to meet the expected volumes in years to come (CEPS, 2018).

Despite a higher complexity, the recycling process of lithium-ion batteries is conceptually similar to that of WEEE and can be schematically divided in three different processes: pre-treatement (mainly mechanical), pyrometallurgical and hydrometallurgical processes. However, in fact these are not alternative methods but rather methods used in combination with each other (CES, 2019).

The **REECOVER** (Grant Agreement ID: 603564) project aimed to contribute to European security of supply of Rare Earth Elements (REEs), bringing forward SME competence and business opportunities in the REE recovery area, as well as strengthening ties between SMEs and innovative research- and education institutions. As such, the project has developed, demonstrated and assessed the viability of recovering REEs, primarily Dysprosium (Dy) and Neodymium (Nd), that are especially critical to the European economy - from two types of industrial wastes:

1. Apatite tailings from the iron ore industry
2. Magnetic waste material from the WEEE recycling industry

These two waste streams were chosen because of:

- their complementarity in characteristics, giving specific demands on the recovery technologies to be developed;
- closed-loop-recycling ambitions and resource efficiency targets: REEs from raw materials largely end up in WEEE-waste or in mining waste, and instead of being deposited in tailing dams or by smelters as slags/dust, they can become valuable REE-based products for further use.

The REECOVER project has developed routes to valorise both apatite tailings and magnetic/ferrous fractions of WEEE waste.

CABRISS (Grant agreement ID: 641972) main vision is to develop a circular economy mainly for the photovoltaic, but also for electronic and glass industries. It consists of the implementation of recycling technologies to recover indium (In), silver (Ag) and silicon (Si) for sustainable PV technology and other applications. The originality of the project relates to its novel cross-sectorial approach associating Powder Metallurgy (fabrication of Si powder-based low-cost substrate), PV industry (innovative PV Cells) and the recycling industry (hydrometallurgy and pyrometallurgy).

CABRISS five main objectives are:

- to develop industrial symbiosis by providing raw materials as feedstock for other industries;
- collect up to 90% of the PV waste throughout Europe (as compared to the 40% rate in 2013);
- retrieve up to 90% of the high value raw materials from PV cells & panels (silicon, indium & silver);
- manufacture PV cells and panels from recycled raw materials achieving lower cost (25% less) and at least the same performances (i.e. cells efficiency yield) as by conventional processes;
- involve EU citizens and industry.

The **RELCD** (Grant agreement ID: 508212) project aimed at developing novel reuse and recycling methodologies in order to avoid the landfill deposition and incineration, which are the main method for LCD disposal, to significantly reduce greenhouse gas (GHG) emissions associated with the incineration as well as contamination of wastewater from landfills.

Specific objecyives of RELCD project were:

1. identify a cheap and fast test methodology to verify whether the obsolete or excess LCDs were still working
2. develop a technology for the refurbishment of working LCDs and their reintegration into repair and in exemptions in production processes
3. identify a test method to detect hazardous substances in liquid crystal (LC) mixtures
4. develop an ecologically efficient disassembly and recycling technology for the non operating LCDs that would fulfil the WEEE Directive
5. develop, implement and test an integrated pilot plant system incorporating the proposed technologies
6. examine possible improvements of the existing LCD design and production in order to improve the sustainability of the products' life cycle.

Numerous treatment technologies were assessed considering various parameters. Manual dismantling achieved the best results and a relevant strategy was formulated. In addition, mechanical treatment was selected as the most feasible recycling option for LCDs without mercury (Hg) lamp recycling. The functionality test layout was prepared and examined under different scenarios, while special LCD model equipment was developed and evaluated using various LCD types.

The main output of the RELCD project consisted in the development of guidelines for sustainable LCD design, production and recycling. An information platform, which would remain operative after the project completion, was also developed.

The **ORAMA** (Grant agreement ID: 776517) project focuses on optimising data collection for primary and secondary raw materials in Member States. A cornerstone to the EIP on Raw Materials is the development of the EU knowledge base on primary and secondary raw materials, commenced by a series of European-funded projects.

As the next iteration, ORAMA addresses specific challenges related to data availability, geographical coverage, accessibility, standardisation, harmonisation, interoperability, quality, and thematic coverage in Member States.

ORAMA analyses data collection methods and recommendations from past and ongoing projects to identify best practices, develop practical guidelines and provide training to meet specific needs. These actions will demonstrate how to improve datasets for mineral occurrences, minerals intelligence data, economic, technical, environmental and social data for primary and secondary raw materials.

For primary raw materials, the focus is on harmonisation and improved coverage of spatial and statistical data, ensuring compliance with the INSPIRE Directive where appropriate. For Mining Waste, Waste Electrical and Electronic Equipment, End of Life Vehicles and Batteries, the focus is on developing ‘INSPIRE-alike’ protocols. The unified data model from the Minerals4EU and ProSUM projects will be applied to the datasets and outcomes will be combined with primary raw materials data. ORAMA will demonstrate how to create more robust Material Systems Analysis studies and reliable Sankey diagrams for stocks and flows of specific raw materials. Information is made accessible and compatible with the JRC's Raw Materials Information System to feed, for instance, future Raw Materials Scoreboard and Criticality Assessment studies.

In the long term, ORAMA empowers the wider EU raw materials community with necessary facts to support policy decisions and sustainable investments in the primary and secondary raw material industries.

The **ProSUM** (Grant Agreement ID: 641999) project developed the very first EU-wide and open-access Urban Mine Platform (UMP) located at www.urbanmineplatform.eu. This dedicated web portal is populated by a centralised database containing all readily available data on market inputs, stocks in use and hibernated, compositions and waste flows of electrical and electronic equipment (EEE), vehicles and batteries (BATT) for all EU 28 Member States plus Switzerland and Norway. The UMP's user-friendly design features dedicated applications, allowing the user to select and produce charts and to download resulting data 'on-demand' in a quick manner. The knowledge base is complemented with an extensive library of more than 800 source documents and databases. With the ability to view the metadata, methodologies, calculation steps and data constraints and limitations are made explicit, allowing the user to review key information and to get an idea of the data quality of the sources used for this massive prospecting effort.

ProSUM – "prosum" is Latin for "I am useful" – provides a factual basis for policy makers to design appropriate legislation, academia to define research priorities and to identify innovation opportunities in recovering CRMs for the recycling industry. The EUIN enables interdisciplinary collaboration, improves dissemination of knowledge and supports policy dialogues. A consortium of 17 partners, representing research institutes, geological surveys and industry, with excellence in all above domains will deliver this ambitious project.

C-SERVEES (Grant agreement ID: 776714) aims to boost a resource-efficient circular economy in the electrical and electronic equipment (EEE) sector through the development, testing, validation and transfer of new CEBMs based on systemic eco-innovative services that include: eco-leasing of EEE, product customization, improved WEEE management and ICT services to support the other eco-services. ICT tools will be developed as the driver of the proposed eco-innovative services to take full advantage of the potential and synergies of two major revolutions of our time: the circular economy and the Industry 4.0.

The project will thus contribute to transform the E&E sector into circular and 4.0, raising new opportunities for end-users (such as their involvement in design or the access to a product as a service) and for social and solidarity economy (conducted by NGOs which employ people at risk of social exclusion to repair and prepare WEEE for re-use). The techno-economic, environmental and social viability of the new CEBMs will be validated through demonstrations dealing with four target products belonging to different EEE categories: large household appliances, IT equipment, telecommunications equipment, and consumer equipment.

LITHOREC (German Federal Ministry of Environment, 2012-2014) projects aimed to develop a new recycling process for lithium-ion batteries from electric and hybrid electric vehicles with a focus on energy efficiency and a high material recycling rate. The developed process route combines mechanical, mild thermal and hydrometallurgical treatment to regain nearly all materials of a battery system

LITHOREC is the only EU project that has been designed to develop and scale up a complete recycling process for electric car batteries. The result has become a process with a very high recycling rate of most materials in several different chemistry. The project has led to a facility being set up which has been taken over by the company Dusenfeld.

AMPLiFII (UK Governemnt, 2014)(UK funded project) is a two year Innovate which aims to create sustainable supply and manufacture of battery packs for hybrid and electric vehicles in the UK.

The project aims to design a flexible, modular battery architecture, developed for both high power and high energy requirements. This will allow supply chain partners to combine demand from multiple lower volume markets to create economies of scale.

The pilot line at WMG has been developed as part of the AMPLiFII project in order to test manufacturing processes, demonstrated at automotive production rates and quality.

4.10 Industrial Symbiosis: Case Studies

TRIS (TRIS, INTERREG EUROPE, 2016-2021). The challenge is to allow a systemic absorption of IS in 5 European regions, supporting policy makers to increase the competitiveness of their SMEs by introducing IS practices. Objectives: The overall objective is to identify and analyse the barriers and/or enabling factors to the widespread and durable adoption of Industrial Symbiosis practices. The exchange and mutual learning based on partners' previous experiences and practices will provide each region with a number of examples of solution to effectively overcome such barriers. Meaningful outcomes: Building a cooperation culture in the stakeholder groups; Standardize IS practices into regional policy instruments; Reaching out to more SMEs, supporting their business with new IS cases/projects, preventing industrial waste production, testing new governance models; Bringing IS to a higher position in the European political agenda.

SIMVAL (SIMVAL, Agencia Valenciana de Innovaciòn (AVI)- regional programme, 2018-2019). The implementation of the industrial symbiosis between productive sectors throughout the Valencian Region, in order to align industrial production with the principles of the Circular Economy and to support related regional national and European initiatives and policies, is the main aim of this regional project. Objectives: SIMVAL aims to become a single platform that acts as an umbrella and brings together all policies and initiatives of private, public or public-private nature in the Valencia Region in terms of circular economy.

FISS (FISS, International development – Finland, 2013-ongoing). Industrial Symbiosis in Finland - FISS (Finnish Industrial Symbiosis System) is a concrete tool for promoting the circular economy. FISS is a collaborative operating model that helps companies and other actors to improve the mutual utilization of resources and to create new business. Objectives: The aim is also to increase the value added of materials and create new competitive products and services. Meaningful outcomes:Motiva coordinates FISS operations in Finland and brings together a network of regional actors to connect resource providers and users in the field.Currently (May 4, 2017) operations are already underway in twelve provinces and more than 600 companies are involved.

TEEZ (TEEZ, Regional Economic Development through indus-trial symbiosis, 2013). This project is a 'physical' manifestation of action in favor of industrial symbiosis. Birmingham was one of the first cities to adopt a pro-active industrial symbiosis approach to develop a medium and long-term strategy for sustainable economic development for the Tyseley Environmental Enterprise Zone (TEEZ). Objectives: The effect is to keep resources circulating in the economy for longer, leading to the generation of economic, environmental and social benefits. Meaningful outcomes: Economic, social and environmental impact can be quantified:

- 400-500 direct jobs (and further jobs related to investment)
- 55,000 tonnes per annum of carbon reduction
- Cost savings for existing companies in excess of £1.9M per annum
- Additional revenue for Birmingham-based businesses of £8-10M per annum
- Total GVA impact of circa £12-15M* per annum.

Burnt Mills Industrial Estate (BurntMillsIndustrialEstate, Local Government support - Basildon Borough Council, UK, 2016). The study established that the industrial demographic and resource availability at the Estate made it a suitable area for transformation using Eco-Industrial Park principles. The report highlighted a priority list of key materials available for reuse including wood, secondary aggregate materials, plastics, and waste electronics and electrical equipment (WEEE). Objectives: the development of a plan that identified where immediate opportunities existed for the recovery of valuable materials and the potential for generating low carbon energy, creating jobs and promoting green business growth. Meaningful outcomes: In the short term, the study identified immediate opportunities to develop local markets for secondary materials so existing materials are kept in productive use for as long as possible. On a five-year implementation plan the benefits to achieve could be as follows:

- £2.2Million of cost savings for Burnt Mills businesses
- £142 Million of new private investment
- 187 new jobs
- 381,200 tonnes of CO2 reduction
- 131,700 tonnes of landfill diversion

In the long term, the study identified opportunities for the Estate to build a Sustainable Resource Recovery Hub and become self-sufficient in terms of its energy and utility provision.

CHINA, Low Carbon Strategy for Hubei Province (CHINA, Wuhan's Strategic Plan for Integrated Urban Development, 2017). This project focused on policy engagement with Wuhan Development Reform Commission to elevate the discussion to a strategic level through the government planning process. Objectives: The main aim of the project was to develop a roadmap to deliver a minimum of 200,000 tonnes of landfill diversion with associated 20,000 tonnes per annum (tpa) of CO2 emissions avoided. Meaningful outcomes: The outcome provided a substantially greater and longer-term carbon reduction than a one-off purchase of carbon credits in the market. Policy recommendations to Wuhan DRC that incentivize circular economy practices and a lower carbon foot-print in Wuhan's construction industry. Map of the potential to reduce carbon & cost while delivering the infrastructure in the Wuhan 2017 plan. Analysis of existing policy enabling or creating barriers to industrial symbiosis delivery.

MI-ROG (MI-ROG, National Government support – Highways England, 2013-ongoing). MI-ROG serves as a platform to show how industrial symbiosis improves major infrastructure projects across utilities. Objectives: The Major Infrastructure–Resources Optimisation Group (MI-ROG) has been founded in 2013 as a forum for the UK's infrastructure operators to collaborate across the circular economy theme and to meet the challenge of delivering major infrastructure in a constrained economy. Meaningful outcomes: The group benchmarks approaches, shares best practice and collaborates across projects, seeking greater resilience and efficiencies with planning, development and delivery of major programmes.

National Industrial Symbiosis Programme (PNSI - France) (NationalIndustrialSymbiosisProgramme, International development-France, 2015-2017). Technological, technical, tool training, support and delivery to support industrial symbiosis in France. PNSI was deployed in Auvergne-Rhône-Alpes, Brittany, Normandy and New Aquitaine and contrary to previous experiments (which relied on the exhaustive referencing of the incoming and outgoing flows of companies through dedicated visits) PNSI applied NISP® methodology of direct contact with companies based on workshops. 17 workshops bringing together more than 550 companies and 138 synergies had been implemented by July 2017. The project highlighted bureacratic barriers to industrial symbiosis advancement.

EUR-IS (EIT-KIC) ((EIT-KIC), Climate KIC, 2012-2013). The impact of industrial symbiosis as an innovation platform has been demonstrated by establishing enhanced methodologies and approaches in 3 economies i.e. Central Hungary, Lower Silesia, UK Midlands and connecting them to expertise and knowledge from the Netherlands CLC. A number of models/tools for deployment of industrial symbiosis as an innovation platform that could be rolled out across the Climate KIC network has been established from the project. The project firmly established the link between industrial symbiosis and innovation.

3GF Industrial Symbiosis Public Private Partnership Track (3GF, Global Green Growth Forum, 2013-2016). ISL is the only SME to have coordinated and hosted a track at the Global Green Growth Forum (3GF), leading on industrial symbiosis. Institutions play a major role in advancing discussions and exploring practical ways to scale up industrial symbiosis activity to meet inter alia SDGs. Cooperation with global institutions such as 3GF (now P4G) highlight industrial symbiosis as an effective means to tackle key global challenges such as material security, climate change mitigation, eco-innovation and green growth.

Industrial Symbiosis Service (ISS) (ISS, INI, Invest Northern Ireland, 2007-ongoing). The ISS is the world's longest running facilitated industrial symbiosis programme based on the NISP® model and delivering industrial symbiosis across Northern Ireland. ISL provides the project with a licence for the implementation of our proven NISP® methodologies and supporting documents, and a license to SYNERGie® software to support data gathering and analysis. ISL provide technical support to assist in the creation and identification of synergies and to advance the project partners from a technical perspective.

Cooperation fostering industrial symbiosis: market potential, good practice and policy actions (Cooperation1). Objectives: Identification of successful factors and issues for the Industrial Symbiosis implementation. Evaluation of the actions supporting Industrial Symbiosis. Evaluation of the interventions contribution to scaling up and promoting IS initiatives at EU level. Meaningful outcomes: The types of industrial symbiosis analysed included: self-organised activity, as the result of direct interaction among industrial actors; managed networks, that have a third party intermediary, coordinating the activity. Managed networks included facilitated networks and planned networks. In addition, an overview of potential markets for industrial symbiosis was provided as well as the main initiatives implemented in Europe with their results.

DG GROW Cooperation Fostering Industrial Symbiosis DG GROW (Cooperation2, CLIMATE KIC, 2017-2018). The investigation of the role of industrial symbiosis coordination and facilitation nodes and to assess the potential to scale up through the creation of an EU level platform to enhance the performance of existing networks were the main objectives of the project. The study concluded that analysis of data relating to industrial symbiosis is highly suggestive of large potential savings and market potential. Trying to understand why this market potential remains under-utilised, the study concludes that industrial symbiosis initiatives experience market failures and are often dependent on the policy environment.

Increased efficiency in the use of materials to deliver future investment (Increasedefficiency, Highways Agency, 2013). Significant material efficiency savings and cost reductions for the Highways Agency (HA) have been identified as part of a scheme which applied industrial symbiosis for the planning and execution of construction projects. The study highlighted opportunities for the HA to save three percent of its capital costs on planned schemes and identified potential threats to the supply certain critical materials which could be addressed through improved communication with the supply chain. Lessons learned on communication and training of industrial symbiosis down the supply chain.

4.11 Best/Good Practices Industrial Symbiosis examples

- **Suiker Unie GmbH & Co. KG in Anklam, Mecklenburg-Western Pomerania/Germany**
  The company runs the only sugar factory in Mecklenburg-Western Pomerania. Various companies in the region benefit from the by-products (bioethanol, biogas, cattle feed, etc.). (Source: https://www.itc-bentwisch.de/itc-aktuell/2019/mit-symbiosen-zum-besseren-unternehmen/ ; Homepage: https://zuckerfabrik-anklam.de/)
- **Veolia Umweltservice Nord GmbH, Germany**
  The company runs a mechanical-biological waste treatment plant on the industrial area of Rostock Port. At Vattenfall, the non-recyclable components are recycled in a substitute fuel plant with combined heat and power. (Source: https://www.itc-bentwisch.de/itc-aktuell/2019/mit-symbiosen-zum-besseren-unternehmen/;
  Homepage: https://www.veolia.de).
- **The commercial and industrial area "Steegener Chaussee“ in Hagenow, Mecklenburg-Western Pomerania/Germany**
  The commercial and industrial area is a pioneer for regenerative energy production and energy efficiency in the region. Two resident biomass power plants produce more electricity than is needed on site and cover more than 50% of the heat concumption in the area. In addition, resident companies from various industries are commited to sustainable and efficient energy use. (Source: https://www.itc-bentwisch.de/itc-aktuell/2019/mit-symbiosen-zum-besseren-unternehmen/
  Homepage: https://www.hagenow.de/wirtschaft/industrie-und-gewerbeflaechen.html)
- **TechnologieRegion Karlsruhe**
  Regional recycling network with 40 to 50 players, with an exchange of organic and mineral co-products. (Source: https://www.oekologisches-wirtschaften.de/index.php/oew/article/viewFile/1360/1343
  Homepage: https://technologieregion-karlsruhe.de/startseite.html)
- **Verwertungssystem Ruhrgebiet**
  Regional recycling network, including a steel mill, power plant and manufactures of building material that exchange co-products and share steam and energy. (Source:

https://www.oekologisches-wirtschaften.de/index.php/oew/article/viewFile/1360/1343).

- **Bioenergie- und Rohstoffzentrum Dormagen**
Exchange of co-products and use of energy cascades between bioenergy and raw material center, local companies, universities and public institutions. (Source: https://www.oekologisches-wirtschaften.de/index.php/oew/article/viewFile/1360/1343).
- **Verwertungsnetz Oldenburger Münsterland**
Regional recycling network with exchange of co-products, with the help of a regional recycling information system and a recycling agency. (Source: https://www.oekologisches-wirtschaften.de/index.php/oew/article/viewFile/1360/1343)
- **Industriegebiet Heidelberg-Pfaffengrund**
Industrial area with small and medium sized companies from the metal processing, chemical, electronics and paper industry with the aim of closing material flows and striving for a local circular economy. (Source: https://www.oekologisches-wirtschaften.de/index.php/oew/article/viewFile/1360/1343
Homepage: https://www.heidelberg.de/hd/HD/Arbeiten+in+Heidelberg/Industrie_+_+Gewerbegebiet+Pfaffengrund.html)
- **Region Mittleres Ruhrgebiet**
Regional recycling network with 30 car dealerships working together on solid and liquid waste as well as typical materials from repair shops. (Source: https://www.oekologisches-wirtschaften.de/index.php/oew/article/viewFile/1360/1343)
- **Zero Emission Parks: Bochum, Bremen, Eberswalde, Kaiserslautern**
The research project aims at a process model and design recommendations for the development of sustainable industrial and commercial areas, using the example of the four locations Bremen, Bottrop, Eberswalde and Kaiserslautern. (Source: https://www.oekologisches-wirtschaften.de/index.php/oew/article/viewFile/1360/1343
Homepage: http://www.zeroemissionpark.de/)
- **ValuePark**
Eco-industrial park with companies from the chemical industry and the plastic production with shared use of facilities and services. (Source: https://www.oekologisches-wirtschaften.de/index.php/oew/article/viewFile/1360/1343
Homepage: https://de.dow.com/de-de/standorte/mitteldeutschland/valuepark)
- **BASF**
The BASF network is designed for the efficient use of energy and resources. Excess heat in a production plant can be used as energy in other plants. Exhaust gases or by-products from one company serve as raw materials for another. This enables the reduction of emissions and waste while saving resources. (Source: https://www.basf.com/global/de/who-we-are/strategy/verbund.html)
- **Georg Fischer Automobilguss GmbH & Nestlé Deutschland AG Maggi Singen**
The Maggi plant in Singen uses the waste heat from the cupola furnace of the Georg Fischer Automobilguss GmbH to produce saturated steam for its production facilities. In this way, the CO2 emissions are reduced and energy is saved. (Source: https://www.energieatlas-bw.de/-/georg-fischer-automobilguss-gmbh-und-nestle-deutschland-ag-maggi-singen)
- **Chemiepark Bitterfeld-Wolfen**
Several companies of the chemical industry are interconnected through a modern local cluster. The different companies share and change ressources with each other. In this

way, waste material and emissions are reduced. (Source: https://www.chemiepark.de/der-chemiepark/stoffverbund/
Homepage: https://www.chemiepark.de/der-chemiepark/stoffverbund/)

- **Kupferkonzern Aurubis AG & enercity Contracting Nord GmbH**
  In cooperation with enercity Contracting Nord GmbH, the copper group Aurubis AG provides part of the waste heat generated in the company for the supply of the eastern harbour city in Hamburg. In this way, CO2 emissions are saved. (Source: https://www.ressource-deutschland.de/fileadmin/user_upload/downloads/kurzanalysen/VDI_ZRE_Kurzanalyse_Nr._22_Ressourceneffizienzpotenziale_von_Gewerbegebieten_bf_01.pdf
  Homepage: https://www.enercity-contracting.de/ueberuns/enercity-contracting/enercity-contracting-nord/index.html)

4.12 Major conclusions on Industrial Symbiosis across sectors

The analysis focused on IS has highlighted the most concrete examples both in case studies and in research projects aiming at optimizing resources use and to reduce the quantity of by-products/waste generated in a “closed loop” in order to improve the environmental and economic performances. The involved symbiotic transactions include: waste utilization as inputs of other industries, transactions of utilities or access to services, and cooperation on issues of common interest. These result in higher energy efficiency and in achieving higher results in the 4R (Reduce, Reuse, Recycle and Restore) approach for the waste management.

The creation of synergies among companies can allow developing successfully IS as well as providing benefits to all parties. In this process, companies develop a trust bond facilitating the supply resources. On the other hand, implementation of the symbiosis network can also produce some problems for companies. The analysis of the literature, case studies and projects in different sectors involved in the SPIRE-SAIS project has highlighted that the synergies involved by different industries can reduce the vulnerability of the network, through the capacity to adapt in order to increase the robustness of an existing industrial symbiosis network and to reduce the possibility of failure.

The Energy Intensive Industries are mostly committed to be involved in IS as the implementation of these measures can make them more efficient and can reduce the negative effects of the process, in terms of energy efficiency and environmental impacts. On this subject, the analysis of industrial symbiosis case studies, already implemented or with potential to be developed IS, has proved to be a strong ally for the achievement of environmental, economic and social objectives. In addition, the large number of recent activities focused on IS in the different analysed sectors have shown as, although this process started in the last few decades, this ongoing process is growing rapidly.

Ongoing and future researches on IS are focusing on the impact quantifications and existing synergies improvements as well as on the creation of new symbioses. Furthermore, it is important to overcome barriers and to quantify the total impact of this practice on companies, the environment and society, by considering different characteristics of the network and particularities of the region involved. This will result in decision-making methods for the final decision-making process.

Going into more details, results on Cross sectoral developments of IS can be summarized as follows:

- Use of recycled products as raw materials for manufacturing new products;
- Transformation of materials from one or more used products into a new product, produced by a third company with a cost reduction;
- Transaction of services, public services between industries to improve resource efficiency;
- Product service system offering solutions for marketable set of common products and services;
- Creation of data management opportunities allowing product customization;
- Significant reduction in production costs, due to the reuse of by-products and wastes;
- More jobs creation resulting from cost reductions;
- A network providing services to external customers for implementing new business and cooperation model solutions for recycling and/or exploitation of raw materials;
- Tools supporting companies to practical measures to be aligned with the concepts of IS;
- Decision support tool for flexibility management, providing accurate scenarios for maximizing the benefits of by-products use and valorization;
- Increase of sustainable development in a region, due to waste/by-products reduction;
- Guidance to local and regional authorities;
- Promotion of public dialogue process to ensure the implementation of regional action plans;
- Fostering interregional learning and capacity building learning events.

Further investigations will create new opportunities for encouraging new synergies across sectors. In this context, it is necessary to make sectors and policy makers aware of what has already been done on IS activities and what has hindered cooperation. This can pave the way for the creation of new symbiosis synergies as well as for further developments of future scenarios, taking into account material scarcity, decarbonization of industrial processes, and stricter environmental policies. Furthermore, supporting EIIs in the transferability of solutions across sectors will be crucial, particularly in areas with high potential, by identifying barriers, and by developing strategies to help overcome these barriers, by promoting solutions utilized successfully across sectors. This will allow for new decision-making approaches in order to achieve new and strategic objectives.

5 Energy Efficiency across sectors

Currently, 84% of the worldwide energy still derives by fossil fuels, with 27% coming from coal (Rapier, 2020). In this context, substantial changes should be provided to policy and technological approaches concerning primary energy usage. In particular, the development of low-carbon technologies and the adoption of renewable energy sources will contribute to reduce GHG emissions (e.g. 38% of CO_2) and, consequently, the global warming. In addition, carbon capture and storage and renewable energy technologies could respectively contribute to 19% and 17% of emissions reduction. Furthermore, the application of new technologies can help to increase energy sustainability and economic development (International Energy Agency , 2009).

In the context of EU, regulations to reduce industrial emissions, improve EE, and encourage renewable energy were introduced (European Parliament and Council, 2012), in order to improve economic competitiveness and sustainability of the European economy, as well as to reduce emissions and energy dependency, and to increase security of supply and job creation. The recent 2030 Climate and Energy Policy aims to achieve the 40% reduction of GHG emissions to reach a competitive low-carbon economy in 2050 (European Commission, 2011), achieving the reduction of GHG emissions by 80–95% (compared to 1990 levels) by 2050, including the increase of competitiveness and security of supply (European Commission, 2012). In addition, by promoting EE practices, imports of fossil fuels can be reduced, leading to energy security in a cost-effective manner and resulting in positive achievements of gross domestic product (GDP) and employment (European Union, 2016).

Some recent EU policies and regulations aim to pave the way to introduce the new growth strategy, such as the EU's 2020 strategy for smart, sustainable, and inclusive growth, based on climate and energy efficiency (European Commission, 2010). On this subject, the "20-20-20" targets include: 20% cut in GHG emissions compared to 1990 levels; production of 20% of EU energy through renewable resources; 20% improvement in EE of the EU's primary energy consumption (Council of the European Union, 2007). A new directive was proposed in 2011 and the Energy Efficiency Directive (EED) (2012/27/EU) was adopted in 2012 (European Parliament and Council, 2012) to revoke the previous Energy Services Directive. This included also legal obligations for establishing energy-saving schemes in EU member states; provisions on the setting of EE targets, general EE policies, energy audits, combined heat and power, management systems for enterprises, consumer behavior, etc.

As EIIs (e.g. steel, chemical, and cement sectors) are fundamental for the European economy, it is crucial their decarbonization and modernization. Improving their EE can be achieved by implementing different measures such as "soft" measures (e.g. good management, education, and behavior changes) (Finnerty, et al., 2017) and "hard" measures (e.g. investments in EE, such as upgrades or new technology installations). However, as in the steel and chemical sectors their energy consumptions, due to an increase in steel production (ICF, 2015), breakthrough technologies implementation will result in flattening energy consumption from 2030 to 2040 (Malinauskaite, et al., 2019). On the other hand, in the non-ferrous metals sector the production will decrease because of the lack of new EU investments in production capacity and expansion of production outside the EU and because of the production increase of secondary metal through improved recycling and recovering useful scrap metal. Furthermore, the non-metallic mineral sector will be moderately flat by 2050, while lime and ceramics sector will slightly decline, glass sector will be stable, and cement production will slightly increase (ICF, 2015). By showing different strategies to implement energy-based IS synergies, including drivers, barriers, and enablers of business development from technical, economic, regulatory, and institutional perspectives, it was highlighted that energy-based IS is one of the pioneering fields in order to achieve the energy transition in the CE context (Fraccascia, Yazdanpanah, van Capelleveen, & Yazan, 2021). As a whole, EIIs, as the European largest energy consumers, need further investments to achieve the EE target. However, the main issues to achieve their competitiveness are represented of the high energy costs and the energy cost disparities across EU member states and plants. In this context, as global energy needs are changing significantly, companies need to adjust their strategies to maintain their competitiveness in this evolving landscape. The EE activities will contribute to reduce carbon emissions to supporting the clean energy transition, to pave the way to the decarbonisation of EIIs while integrating renewable energies within their production processes and activities. In particular EE, through the implementation of new technologies and approaches, will play a key role in achieving global climate objectives (Khaleel, et al., 2023). In addition, digital tools by automating processes help to improve EE in the context of energy transitions, climate change, economic recovery, and job creation. Leveraging digital technologies, such as artificial intelligence, predictive analytics, and cloud computing, aim to track energy usage patterns across multiple sites in real-time, allowing companies identifying new opportunities for further improvement. In addition, digital tools are crucial for providing a platform for collaboration between industries and between stakeholders on sustainability initiatives for reaching further improvements related to EE. In this context, governments but also policy instruments, ranging from energy standards to incentives for adopting renewable energy, play a crucial role in improving energy efficiency across sectors. Market mechanisms also play an important role, influencing industrial companies to prioritize EE not only as a regulatory compliance measure but also as a competitive advantage (Karduri & Ananth, 2023).

5.1 Iron and Steel Sector

5.1.1 State of the art of the Energy Efficiency in the Steel Sector

Although steel products need energy to be produced, they produce also savings over the life cycle of the product. In addition, steel can also reduce product life cycle energy use and emissions by maximising the value of resources by improving product design, recovery and reuse, remanufacturing and recycling. Energy efficiency has been identified as a key driver for the steel and iron industry (Wu, Wang, Pu, & Qi, 2016). In the energy-intensive manufacturing industries as steel and iron ones, the energy can account for up to 25% of operating costs representing a very strong factor for increasing the competitiveness (IEA, 2014) (Bunse, Vodicka, Schönsleben, Brülhart, & Ernst, 2011). However, over the last 40 years the EU steel industry has reduced its energy consumption by 50%, due to higher scrap recycling levels and a decrease in production (European Commission, 2014).

During the past 20 years, great efforts are made from the steel industry in order to reduce the energy consumption of its processes and in all the countries iron and steel manufacturing presents improved efficiency (He & Wang, 2017). The improvement of the socio-economic and environmental sustainability of its processes by promoting any development is ever more committed to the European Steel industry, in order to increase resource efficiency and lower the environmental footprint of the steel production. The European Steel Technology Platform gives the highest priority to the topic of Sustainable Steel Production within its Strategic Research Agenda since 2013 (Birat, Malfa, Colla, & Thomas, 2014). At the same time, the improvement of the product quality arises in order to face the increasing competition.

In addition, in the last few decades, it has reduced its energy intensity by 60% (U.S. Energy Information Administration, 2019). Although the steel sector is an energy-intensive industry, currently, sophisticated energy management systems have been developed in order to ensure efficient use and recovery of energy throughout steelmaking processes to be used within the steelworks boundary or exported from the site. Energy efficiency in steelmaking is fundamental to ensure the competitiveness of the whole sector and to minimise environmental impacts, such as greenhouse gas emissions. Steel saves energy through its 100% recyclability, durability and lightweight potential (worldsteel, 2021). In this context, some technologies began to be implemented in order to reduce CO_2 emission, such as top gas pressure recovery turbines (TRTs) and combined cycle power plants (CCPPs). As the iron and steel industry contributes to ~8% of current global anthropogenic CO_2 emissions, >2800 Mt CO_2 per year (International Energy Agency, 2016), its challenge is mainly focused on technologies implementation for low-carbon steelmaking. Recovering energy and re-using materials from waste streams, high-temperature slag as well as re-investing the revenues for carbon capture and storage is one of the main challenges of this sector. In particular, based on energy recovery and resource recycling of glassy BF slag and crystalline steel slag, a reduction of 28.5 ± 5.7% CO_2 emissions can be achieved, generating also revenues. In addition, this results in reducing to the sectoral 2°C target requirements in the steel sector before 2050. By using revenues to fund carbon capture and storage (CCS), equivalent CO_2 emission to the sectoral 2°C target requirements is expected to be reduced in this sector before 2050 without any external investments, leading to the long-term decarbonisation target and sustainable development of this sector. In this context, looking at climate and energy policies and implementation of low-carbon electricity generation in countries that produce steel from coal, the global steel industry does not appear to be in a good position to achieve net zero emissions by 2050 (Arens, Åhman, & Vogl, 2021). Although countries agree on long-term CO_2 reduction targets and medium-term renewable energy targets, and they have already started to implement non-hydro, non-biofuel renewable electricity generation (NHB-RES), only the EU-28 meets these indicators. In particular, all other countries do not show a strong commitment to the energy transition related to climate and energy targets or are lagging in implementing low-carbon electricity.

According to the “Best Available Techniques (BAT) Reference Document for Iron and Steel Production” (Roudier, Sancho, Remus, & Aguado-Monsonet, 2013), the optimization of the off-gases management in an integrated steelwork represents a key issue of energy efficiency. Although off-gases are currently used outside the steel production, such as in power plants, heat and steam production, the new developed approaches (e.g. Decision Support System) could be exploited for the application in other industrial sectors. Process gases are a very valuable resource: these gases can be considered as an intermediate by-product for the production of other valuable energy carriers or products with an associated environmental benefit. Especially the process off gas produced during blast furnace operation can be considered as valid substitutes of natural gas, since they are sources of a considerable amount of energy.

In this context, in order to estimate the off-gases production (and related energy content) and demand of the different processes on a short-term horizon (2 hours with a sampling rate of 1 min or 5 min), including energy transformation equipment machine-learning based approaches have been applied (Matino, et al., 2019) (Matino, Dettori, Colla, Weber, & Salame, 2019) . In particular, Echo-State Neural Networks (ESN) and Deep ESN (a specific recurrent neural network) have shown to be very effective for modelling dynamic processes starting from process data being also computationally efficient (Colla V. , Matino, Dettori, Cateni, & Matino, Reservoir computing approaches applied to energy management in industry, 2019). In (Dettori, Matino, Colla, & Speets, 2020) Deep ESN has been applied also to the modelling of nonlinear dynamics typical of complex industrial processes: the forecast of energetic content in blast furnace gasses, produced during the production of hot metal in steelworks and one application of its consumption in the process called Hot Blast Stoves (Cowpers) has been developed. Artificial Intelligence based models have been used in order develop a sequential distributed model predictive controller. A mixed-integer model predictive controller which considers economic constraints and objectives has been applied in order to optimize the energy conveyed by the off-gases in integrated steelworks (A. Wolff, 2019). Moreover, in order to achieve an almost complete use of these gases, their production and consumption can be forecast according to the production plan and to use such forecasting to optimize the gases distribution inside the network by considering possible interactions (Matino, Dettori, Colla, Weber, & Salame, 2019). In the electric steelmaking route, Colla et al. (Colla V. , et al., 2018) have elaborated a series of key performance indicators in order to monitor the efficiency of the gas management and the objectives of the optimization have been defined. In (Matino, Colla, & Baragiola, 2017) , (Matino, Colla, & Baragiola, 2017) and (Colla V. , et al., 2016) scenario analyses are carried out looking for process modifications, in order to improve the sustainability of electric steel production through the exploitation of an assessment and simulation tool based on the definition of Key Performance Indicators and on the Aspen Plus® modelling.

Several studies have been carried out on the Process Integration models with the aims to improve the materials and energy efficiency, together with environmental or economic sustainability for the steel production systems (Porzio G. F., et al., 2014) (Porzio G. F., et al., 2014) (Matino, Fornai, Colla, Romaniello, & Rosito, 2017) (Larsson, 2006). The evaluation of Process integration has been devoted also to the recovery of wastewater (Alcamisi, 2015) (Colla V. , et al., 2017).

Recently, procedures focused on EE were applied to gas network management in steelworks. They included the use of Machine Learning (ML)-based models aiming at optimizing gases distribution, considering possible interactions (Matino I. , et al., 2020) (Matino I. , Dettori, Colla, Weber, & Salame, 2019). In addition, echo-state neural networks (ESNs) and deep ESNs (i.e., specific recurrent neural networks) are used for modelling dynamic processes. Deep ESNs also were applied for modelling nonlinear dynamics of complex industrial processes, such as forecasting energy content in BF gases during the hot metal production (Dettori S. , Matino, Colla, & Speets, 2022). Furthermore, the use of Key Performance Indicators (KPIs) for monitoring gas management efficiency, and for defining overall economic and environmental objectives represent a valuable tool (Colla V. , et al., Assessing the efficiency of the off-gas network management in integrated steelwork, 2018).

Wolff et al. in (Wolff, et al., June, 2019) studied the improvement of the energy efficiency by investigating the improvement strategies for the hot blast stove operation: a mathematical model was developed to evaluate the performance of the hot blast stoves by using a finite differential approximation to represent the heat transfer inside the furnace during operation. Thanks to a control model, the temperature distribution and the state of charge of the hot stoves are estimated and predicted online supporting the plant operator in his decisions.

The importance of joint process and energy management has been highlighted in many literature results (Mazur, Kay, Mazur, & Venne, 2018). In the steel industry, the traditional approach is still production-driven, i.e. first the production is scheduled, then the energy supply is optimized in order to find the best available energy portfolio, which is usually sub-optimal. The combination of the scheduling and the optimization of the energy procurement are formulated as an integrated monolithic optimization model, resulting in intractable problems that require excessive computational time to be solved. Hadera et al. in (Hadera, Ekström, Sand, & Mäntysaari, 2019) used Mean Value Cross Decomposition in order to solve the combined problem by iterating between energy-aware production scheduling and energy-cost optimization and adopted MILP-based models for the formulation of the scheduling problems, while for the energy cost optimization a Minimum-Cost Flow Network has been used. In addition, the use of different machine learning and data processing methods to evaluate the energy efficiency parameters of the EAF process, resulting in complex processes optimization, and energy consumption reduction (Manojlović, Kamberović, Korać, & Dotlic, 2022). Data, from a dataset collected over five years, was split into training and test sets, used for training and evaluation, respectively. Results showed that a data-centric rather than model-centric approach is better for improving model performance. Among other results, employing a data-centric machine learning model to control and optimize main process parameters (with a small economic investment) can provide lower energy consumption for industrial processes.

According to (Johansson, 2015), in the Swedish and iron steel industries the main important barriers for the implementation of the energy efficiency measures were: lack of time, lack of personnel, information not clear by the technology supplier, risk of production disruption, other priorities for capital investments, lack of people with higher education in the energy field and lack of awareness of the potential of engaging employees. He et Wang in (He & Wang, 2017) review the energy use and energy efficiency measures/technologies for the iron and steel industry, summarizing a large number of energy-efficient, cost-effective, and available technologies to help energy managers select areas for energy efficiency improvement. More efficient technologies, energy recovery in the manufacturing process, increased energy conversion efficiency and optimisation of operational practices are some examples of measures in order to improve energy efficiency (Bunse, Vodicka, Schönsleben, Brülhart, & Ernst, 2011). Furthermore, Non-energy benefits (NEBs) represent benefits that are neglected from implementing EEs measures and technologies. The impact of implementing NEBs, such as fossil fuel saving, avoided air and avoided deaths caused by pollution, was identified, quantified and measured (Bin Abdulwahed, 2021). On this purpose, the impact of implementing 20 new EE measures (EEM) in the steel sector was analysed. Results, coming from the the SEEnergies project (sEEnergies, s.d.), as part of the Horizon 2020 Research and Innovation Program, showed significant benefits in BAT scenarios analysed. In particular, the NEB indicator increases the significance of the benefit of recycling, showing emission and fossil fuel reduction, and the indirect impact of deaths from emissions. The lack of available data to quantify other NEBs in the duration of the research represents the main limit of the conducted research.

Concerning new technology implementations, Direct hydrogen reduction produces DRI using 100% H_2 produced from renewable energy, is considered to be the most promising technology to replace the conventional BF ironmaking process. Currently, almost all of the H_2 is produced from fossil fuels and water electrolysis using non-renewable power energy, resulting in a large carbon footprint. Conversely, H_2 produced via water electrolysis, through electricity from renewable sources, is the most effective method to reduce CO_2 emissions (Wang, Zhao, Babich, Senk, & Fan, 2021). Nevertheless, in the short to medium term, other types of clean H_2 will be used as transitional hydrogen energy. But, in the long term, the H-DR process will reduce up to 80–90% of CO_2 emissions, depending on the availability of green hydrogen. For this reason, increased efforts should be made in order to develop low-cost H_2 production technology, improve the direct reduction process, achieve the goal of H-DR, and promote the transition of the steel industry to carbon neutrality. In this context, EAF steelmaking is the key technology for decarbonised steelmaking, due not only to the modification of existing processes for further decarbonisation, but also to new EAF installations to (partly) replace the classical BF-BOF route. In addition, the EAF is the most important example for modular and hybrid heating, combining electric arc heating with burner technologies. H2-enriched direct reduction (DR) is the key decarbonisation technology. Natural gas driven DR is already established in industry mostly outside Europe. New studies and projects are in place in order to provide missing knowledge and data of reduction processes. In particular, digital models can be used to optimise DR furnace design and to optimise the process integration into existing process chains. In addition, simulation tools can be combined with toolkits covering the impacts of product properties on downstream processes and impacts on gas and energy cycles. Concerning decarbonisation, new approaches at EAFs including the use of hydrogen to replace natural gas combustion are developing. In addition, decarbonisation of EAF steelmaking by technologies is developed in order to re-optimise the heating management with maximum heat recovery of off-gas and slag, by using new sensor concepts. Monitoring and control tools will enable the control of decarbonised hybrid heating with maximum energy efficiency. This new synergic concept can support implementation and digitising to speed up the transition of the European steel industry to highly competitive energy-efficient decarbonised steel production. The interest in alternative and non-fossil sources of carbon has been highlighted in some recent analyses relating to the use of biomass and further alternative sources of carbon and energy in steelmaking processes. On the other hand, the production and use of hydrogen is crucial for CO_2 emissions elimination and by the low cost of transport compared to biomethane and natural gas. However, the use of green hydrogen presents some issues to be considered, such as the increase of water consumption and the very high electric energy consumption and soil exploitation. In addition, the increase in renewable energy production for the green hydrogen production represents a serious challenge (Mapelli, Dall'Osto, Mombelli, Barella, & Gruttadauria, 2022). In this context, the increase in the import of hydrogen from steel could be considered as a possible solution. Furthermore, the use of natural gas and CCS represents a favourable scenario particularly in a steelmaking route involving the charging of DRI in the EAF. This appears to be the most plausible solution for the environmental impact reduction of the steel sector.

In the near future, improvements in EE will be achieved through the optimisation of the energy use by implementing the best-available steelmaking technologies in the outdated steel plant or by applying them through technology transfer. In addition, the implementation of breakthrough technologies can lead to major changes in the way steel production, reaching higher improvements also in EE.

In the last 15 years, many research projects have focused on energy efficiency and reduction of CO2 emissions. Nowadays it must be determined that the optimisation of the single processes like EAF, re-heating or rolling lead only to lower percentages of improvement.

5.1.2 Projects on Energy Efficiency co-funded by the Research Fund for Coal and Steel

A lot of RFCS projects have been funded along the last 15 years in issues like energy efficiency as well as CO_2 emissions reduction or optimization of the off-gas management.

EnergyDB (ENERGYDB, RFSR-CT-2013-00027 01/07/2007-31/12/2010) project has been a starting point since the main aim was to develop a database in which the energy consumption is directly assigned to different intermediate or final products by connecting it with production conditions.

In **ENCOP** project (ENCOP, RFSR-CT-2009-00032 01/07/2009-31/12/2013) a reduction of CO2 emissions has been obtained using analysis tools for energy and material flows in integrated steelworks. It was based on the analysis of the energy and mass flows in selected steel plants as well as on both physical and Machine Learning-based modelling. To reproduce the various energy and material flows scenarios, a virtual prototype of integrated steel mill was developed, and ad hoc models and software were applied to assess process performance. In each scenario the total energy consumption and the CO_2 balance were evaluated by applying tools to forecast the energy demand or to compare different operation modes within an integrated approach. A Decision Support System was also developed to help plant managers in off-gases optimal valorisation and CO_2 emissions management and minimization. Advanced optimization approaches were implemented ant tested, including Mixed Integer Linear programming and Evolutionary computation.

GASNET project (GASNET, RFSR-CT-2015-00029 01/07/2015-31/12/2018) aims at supporting the management of the off-gas network in the integrated steelworks by considering environmental and economic objectives through the synchronization of off-gas, steam, and electricity networks, and through an intelligent and efficient consumption of external energy sources (e.g. natural gas). Its goal was maximum valorisation of all the gaseous streams, while minimising the flaring of useful off-gases and the purchase of natural gas, with a consequent reduction of both emissions and costs. Advanced simulation and optimization tools were intensively applied to this aim. Machine Learning-based models were developed in order to forecast on a suitable time horizon the main features of the produced off-gases and the energetic demands of the consuming processes. An optimization solution based on a hierarchical model predictive control approach was developed to optimally distribute the different off-gases steams. These components were embedded into a decision support system for process operators, which is helps them in gas network management and full exploitation of the ML-based forecasting models.

THERELEXPRO (THERELEXPRO, RFSR – CT – 2013 – 00029; 1/07/2013 – 30/06/2016) aims to develop and to improve thermoelectric technology to recover waste heat from steel plants available at low temperature (T< 350°C) and convert it into electricity. A large amount of data has been used in this project, but they were not sufficient to realize electricity production systems at industrial scale and the use of thermoelectric energy production systems, based on the two prototypes developed in this research cannot be used for large electricity production, due to the high cost of electricity produced. However, it has been demonstrated that these systems are able to produce electricity through waste heat harvesting, producing “net electricity” under proper circumstances and then they can be considered suitable, in the near future, for small electric energy productions.

Another project dedicated to the recovery of the off-gases is **PowGETEG** (PowGETEG, GA Number: RFSR – CT – 2015 – 00028 - 01/07/2015 – 30/06/2019): the main aim of this project is determinate the possibilities of thermoelectric power generation using industrial gaseous waste heat at temperatures above 550°C. During the development, new solutions for control, power conversion, heat exchange and protection were designed and investigated. Even the economic evaluation showed that it is not economically viable for large-scale electricity consumers, for smaller companies with higher electricity rates and tolerating higher payback periods this solution could be of interest.

Thanks to **I3UPGRADE** project (I3UPGRADE., RFCS; 01/06/2018-31/12/2021), a running project, an intelligent and integrated upgrade of carbon sources in steel industries through hydrogen intensified synthesis processes and advanced process control technologies is developing. The I3UPGRADE project is focusing on the reduction of steelworks environmental impact exploiting the process gases for the production of methanol and methane. In particular, the idea is the improvement of synthesis processes by adding renewable hydrogen to off-gases. Ml-based process modelling (in particular exploiting Echo-State Neural Networks) is exploited to derive computationally efficient and accurate models, which can be easily embedded into control and optimization schemes. Furthermore, an advanced control system is under development to optimize the distribution of process gases (not used for internal users) between the synthesis reactors and the power plant, the exploitation of hydrogen, the operational costs and the ones related to CO_2 emissions and to estimate the thermodynamic and economic performance of the technologies in different market circumstances. Finally, Multi-Agent Systems are adopted for long term scenario analyses considering future markets situations and volatility. The main results for technological improvement will be the design of innovative reactors for the methane and methanol synthesis, and the development of a dispatch controller. AI and ML-based approaches are being intensively exploited for process modelling, control as well as for optimal management of the gas network.

DYNERGYSTEEL (DYNERGYSTEEL, RFSR-CT-2014-00029; 01/07/2014-31/12/2017) and **ADAPTEAF** (ADAPTEAF, RFSP-CT-2014-00004 01/07/2014-30/06/2017) are two projects in which the self-organizing production by a new combination of resource and energy increases the automation leading to a real time control of production networks. In DYNERGYSTEEL, a new approach for electricity demand monitoring and timely reactions to grid situation to avoid non flexible equipment disconnection and financial fines when deviating from energy contingent has been developed. Marchiori in (Marchiori, et al., 2018) (Marchiori, et al., 2017) shows a first effort to exploit the potential of the integrated through-process approach for managing events coming from the power markets and the transmission network by means of increased negotiation capability supported by new automation tools. In ADAPTEAF, a new adaptive online control for the EAF depending on the properties of the actually charged materials, to optimise the efficiency of the chemical energy input and thus to reduce the total energy consumption and to improve the metallic yield has been set up. Other projects developed within the context of the steel manufacturing for the Electric Arc Furnace (EAF) route and the improvement of the energy efficiency are:

1. **EPOSS** (EPOSS, RFSR-CT-2007-00006 ; 1/07/2007-31/12/2010) : in this project the increase of energy efficiency and productivity during EAF high alloyed stainless steelmaking has been obtained by the development of innovative slag conditioning techniques for slag foaming and adjusted use of all available energy sources.
2. **RIMFOAM** (RIMFOAM, RFSR-CT-2014-00008-1/07/2014-30/06/2017) project whose the main aim was to partly substitute carbon and oxygen with mill scale and other industrial and/or municipal waste for slag foaming purposes in the EAF.
3. **FLEXCHARGE** project (FLEXCHARGE, RFSR-CT-2007-00008 01/07/2007-31/12/2010): the optimisation tools has allowed robust charge mix tools in order to set up and determine the scrap mix for a given steel quality and quantity while minimising cost and energy consumption. Moreover, dynamic mass and energy balances have been adapted to electrical arc furnaces, considering the measurement of the off-gas composition and the mass flow rate and temperature at fourth hole evaluated by virtual (SW) sensors developed in the project
4. **OFFGAS** (OFFGAS, RFSR-CT-2006-00004 01/07/2006-30/06/2009): in this project, the increase of the efficiency of EAF oxygen injection and energy transfer to the scrap and melt was the main objective of this project. A permanent on-line monitoring and control of the EAF process on the basis of off-gas analysis has been implemented.
5. **OPTISCRAPMANAGE** (OPTISCRAPMANAGE, RFSR-CT-2014-00007 1/07/2014-30/06/2017): The project aim was the improvement of EAF process performances, steel quality and cost reduction in terms of metallic yield, energy efficiency, and steel quality following a continuous route of improvement including charge mix and operating practice optimization in a single step.

Other projects related to the steel sector, but in particularly to the steel products and energy efficiency in the buildings have been ETHICS, EEBIS, TABASCO and BASSE.

In **ETHICS** (ETHICS, RFSR-CT-2008-00038 01/07/2008-30/06/2011) project, the evaluation, measurement and making improvements in the thermal and energy performance of steel-clad and steel-framed buildings have been developed. Since the energy efficiency is a key aspect for design and construction of buildings in the future, this project provided scientific data, which prove the high energy performance of current steel constructions and work out details for further improvements to maintain and extend the position of steel products in the construction sector.

In the **EEBIS** (EEBIS, RFSR-CT-2003-00017 01/09/2003-31/08/2006) project, the main aim was to develop technologies and concepts for new steel products and systems for energy efficient buildings; provide physical data on the performance of those innovative techniques which actively regulate energy consumption in buildings; development of the structural systems which use air and water as the medium for cooling; - provide design 'tools' for whole building energy assessments. A European database of the performance of a wide range of thermal bridges in steel cladding, light steel and modular constructions and steel primary structures has been developed by **TABASCO** (TABASCO, RFSR-CT-2011-00028 01/07/2011-30/06/2014) project.

BASSE (BASSE, RFSR-CT-2013-00026 01/07/2013-30/06/2016) project aimed to push technological innovation in steel manufacturing forward by developing a new energy generation steel skin, based in a well-established steel product such as sandwich panels, and robust and increasingly used heat pumping system, which will be integrated and pre-engineered, for plug & play integration in buildings. This will strongly impulse the introduction of energy saving strategies in the building envelope market. A project related to the reduction of the emissions and the maximization of the energy efficiency in the coke oven heating by using intelligent diagnostics and individual wall heating control was **ECOCARB** (ECOCARB, RFCR-CT-2008-00007; 31/07/008-31/12/2011). A regenerator inspection robot was developed and applied under real coke oven conditions as part of a complete evaluation of combustion efficiency, with guidelines to identify combustion problems.

In **TotOptLis** (TotOptLis, RFSR-CT-2010-00003-01/07/2010-31/12/2013) project, the main aim was the development of a through-process integrated approach of material and energy input regarding quality, productivity and costs for process chain optimisation in liquid steelmaking. Real-time monitoring and predictive models, elaborating process and sensor data from different aggregates have been integrated.

I2MSteel (I2MSTEEL, RFSR-CT-2012-00038 - 01/07/2012-31/12/2015) developed a new paradigm for a factory and company-wide automation and information technology for Intelligent and Integrated Manufacturing at steel production has been developed and demonstrated.

WHAM (WHAM, G.A. No. 800654 01/09/2018-28/02/2022) is an ongoing project which aims to optimise water consumption in the steel manufacturing processes by means of a holistic solution combining a flexible on-line monitoring and optimisation platform and innovative water treatment technologies.

In **EnerMIND** (EnerMIND, G.A. 899345; 01/07/2020-31/12/2023), an ongoing project, advanced ML-based data analytics and modelling is applied in order to forecast energy consumptions in the different areas of the electric steelmaking route in order to optimise energy management, reduce consumptions and improve the interaction with the energy market. In particular, EnerMIND project aims at optimizing energy management in steelworks by applying a pioneering software, based on a new IoT/IIoT architecture, able to connect the energy market with the internal energy management. New data-driven models will be developed, through the combination of Artificial Intelligence, Machine Learning and Optimization techniques. These new models can "learn from experience" and will lead to a better plant organization and resource scheduling, thanks to the integration of superior forecasting and reliable capabilities.

RIHANNE (RIHANNE, RFCS; 01/06/2019–30/11/2022) "Reliable Blast Furnace Hearth Management". The focus of project is based on a more reliable BF hearth management in order to improve the productivity, process stability and material and energy efficiency. Objectives: The main objectives of the project include measurements from innovative on-line devices and comprehensive novel models of lining wear, hearth flow, liquid levels and taphole flow through their integration via Big Data Methodology in order to provide straight-forward operator guidelines for smooth and reliable BF hearth operations. Results: The implementation of developed tools several BFs and the application of multiple BFs will ensure that the current state-of-art is utilised and the methods are generally applicable, and also to compare different technologies to determine the best practice.

SafeDewPoint (SafeDewPoint, RFCS; 1/07/2019–31/12/2022) "Acid dew point and corrosion sensors for dynamic waste heat recovery from steel mill flue gases". BF gas, coke oven gas and BOF gas are used in coke plant, sinter plant, hot blast stoves, power plant and reheating furnaces. The flue gas temperature is fixed 10-20 K above the calculated maximal Acid Dew Point (ADP) temperature to prevent corrosion damage. As valuable energy is lost during periods with the lower ADP temperature, there is a potential recovering and reusing for combustion air preheating. Objectives: The project aims at recovering waste heat from combustion of steel mill flue gases through dynamic adjustment of their temperature above the ADP, by inline monitoring of ADP temperature. To prevent damage to the heat exchangers and chimneys if measurement fails, corrosion monitoring is required. Results: A novel inline ADP sensor has been developed and corrosion probes based on the measurement of resistance of a corroding wire have been adapted to steel mill flue gases. Based on measurement signals, dynamic waste heat recovery will be developed and validated in tests. The main outcomes consist in improving the energy efficiency of hot blast stoves, power plants and reheating furnaces by dynamic recovery of up to 20% waste heat from the flue gas using existing facilities. This will lead to significant energy saving in the European steel industry as well as emission reduction in integrated steel plants.

HydroPick (HydroPick, RFCS; 01/06/2019–30/11/2022) "Analysis and control of hydrogen content during steelmaking". The project concerns the analysis and control of hydrogen during steelmaking process, such as secondary metallurgy and continuous casting. Objectives: The project aims at increasing the control of the hydrogen content during the liquid steelmaking steps in order to achieve low target hydrogen contents in the final product with reduction of energy and resource consumption. This concerns investigations on hydrogen pick-up and removal in liquid steelmaking steps, such as secondary metallurgy and continuous casting. Results: Results will be used to derive correlations of hydrogen content with the process conditions during the different treatment, such as ladle treatment and casting via the tundish. Dynamic process models will be set up for the mechanisms and metallurgical reactions of hydrogen pick-up and removal. These models will be used in combination with optimised in situ measurements to monitor and predict the hydrogen content in the liquid steel. This will allow achieving the target hydrogen content in the final product under minimum energy and resource consumption.

BURNER 4.0 (BURNER4.0, RFCS; 01/06/2019 – 30/11/2022) "Development of a new burner concept: Industry 4.0 technologies applied to the best available combustion system for the Steel Industry". Following the recent improvements of combustion systems and burners in the steel sector, that can lead to energy saving, pollutant emissions reduction and process flexibility, the extension of the current technological limits of the combustion systems is necessary. In particular, this concerns different areas to new ones through the application of the Industry 4.0 technologies, such as Additive manufacturing, Internet of Things, Smart Sensors, Big Data Analytics for process optimization and predictive maintenance. Objectives: The main objective of the project is the assessment of impact, the constraints and the benefits of the application of Industry 4.0 technologies to the burners in the steel industry. In particular, it aims at extending the current technological limits in different areas (i.e. Design, Manufacturing processes, Control and process optimization, Operating life and maintenance) to new ones by applying the Industry 4.0 technologies leading to a break-through burner concept for the steel sector. Results: The proposed methods and techniques will lead to further energy savings, emission reduction and process flexibility.

HESS (HESS, RFCS; 01/07/2023-30/06/2026). Objectives: the project aim is to develop a Hybrid Energy Storage System (HESS) using post-mining infrastructure. The inventory of post-mining infrastructure will include both mine shafts and underground workings. The analysis of the possibility of its use for parallel energy storage in: Pumped Storage Hydroelectricity system (PSH), Compressed gas – Air/CO_2 Energy Storage system (CAES) and Thermal Energy Storage system (TES) will be made. The possibility of using geothermal energy and the use and potential storage of CO_2 (CCS – Carbon Capture and Storage) will also be determined. The assumed total energy storage capacity will be min. 30 MWh. On the basis of the energy demand of each HESS component, a method of thermal and mechanical integration of the entire system will be developed. An algorithm for the mutual interaction between the elements of the energy storage system will be developed. Optimal cooperation of the various elements of the HESS will be supervised by an energy router. The router will also manage energy exchanges with the national power grid for the intake of low-cost green energy and peak energy production. The single HESS energy router system should take into account the possibility of cooperation of multiple HESS systems working in a distributed system. Technical and economic and LCA analysis will form the basis for work on the construction of a pilot plant and industrial implementation of the project results.

MultiSensEAF (MultiSensEAF, RFCS; 01/07/2023-31/12/2026) project addresses the steel process and process-chain optimization via instrumentation, detection of properties of products, modelling, control and automation, including digitalization, application of big data, artificial intelligence. Objectives: the overall objective of the MultiSensEAF project is to develop, implement and test multi-sensor systems for an optimized EAF process control. The project objectives include: Development of new scrap proximity sensors integrated in movable head injectors installed and tested at one industrial EAF; Development and implementation of innovative multi-sensor systems for scrap meltdown monitoring in melting phase, slag conditions, thermal status detection and hot heel in refining phase through merging different principles of detection, OES sensors, camera images, focused radar measurement and acoustic measurements at two industrial EAFs; Development of innovative soft sensor for scrap characterization based on a scrap meltdown monitoring using multisensory approach; Development of soft-sensor approach to determine liquid bath decarburization rate and content of C in the bath through off gas detections; Application of improved movable injector operation strategies for optimized scrap meltdown and slag foaming; Testing and integration of the sensor data into existing KPI and model-based process management systems to optimize EAF operation.

5.1.3 Other EU and not EU funded Projects on Energy Efficiency deeply involving the steel sector

In WaterWatt (WaterWatt, H2020 G. A. No 695820; 2016-2019) an energy efficiency evaluation (E3) platform has been developed to disseminate knowledge/know-how on energy efficiency improvements using gaming approach. The tools of the E3 Platform can be used by SMEs and large industrial producers for self-assessment and improvement of the energy efficiency in their circuits. The main aim of this project was to remove market barriers, namely the lack of expertise and information on energy management and saving potential in industrial water circuits. In fact, there is no benchmark for energy consumption in industrial water circuits and no tools for its systematic reduction. Delta (DELTA, H2020 GA No 773960; 2018-2021) ongoing project targets the smart energy grids management and aims at developing a Demand-Response (DR) management platform that distributes parts of the Aggregator's intelligence into a novel architecture based on Virtual Power Plant (VPP) principles. A novel multi-agent based, self-learning energy matchmaking algorithms to enable aggregation, segmentation and coordination of several diverse supply and demand clusters has been proposed and implemented within this project. It will also set the future benchmark for data security by implementing novel block-chain methods and authentication mechanisms as well as by using Smart Contracts. It can be considered as a reference point for the usage of matchmaking algorithms and block-chain methods and authentication mechanisms, even if the project scope is totally far from the specific needs of steelworks. COCOP (COCOP, H2020 Ct No 723661; 2016-2020) project has the objective to enable plant-wide monitoring and control by using the model-based, predictive, coordinating optimisation concept in integration with plant's automation systems. In this project the overall problem is decomposed into unit-level sub-problems, enabling the operators to understand the functioning of the plant as a whole, including the areas traditionally beyond their control, and take better decisions within their part of the process. This project will research and demonstrate this concept on two pilot cases (copper and steel manufacturing process) and analyse the transferability to other two sectors: the chemical and water treatment processing. CHROMIC (CHROMIC, Horizon 2020 – GA No. 730471; 1/11/2017-31/10/2020) is an ongoing project which dealing with the development of new process to recover vanadium, chromium, molybdenum and niobium from industrial wastes. A range of chemical and physical methods will be developed, tested and validated to extract valuable and critical metals from the initial slags in the most sustainable way: economically, environmentally and socially. In SRS project (SRS, POR FESR 2014/2020 – ACTION 1.3.a - COLLABORATIVE RESEARCH 2016-2018), an innovative device for ladle slag processing aimed to re-introducing such product into the Electric Arc Furnace, in substitution of lime has been developed. In RED_SCOPE project (RED_SCOPE, KIC EIT Raw Materials 2016-2019), the development of a flexible economic treatment of complex materials, thereby addressing the issue of removing the increasing amount of impurities and enabling greater reuse of process residues has been carried out.

LoCO2Fe (LoCO2Fe, H2020; 01/05/2015-31/10/2018) "Development of a Low CO2 Iron and Steelmaking Integrated Process Route for a Sustainable European Steel Industry". Over the past decade, the steel industry in Europe has spent a lot of effort in R&D of technologies that help in achieving the EU's CO_2 emissions targets. Several technologies were put forward for further development, one of which is the HIsarna smelting reduction process. Large structural changes were implemented on the HIsarna pilot plant. A new off-gas duct has been installed, a raw materials preparation plant was constructed and an improved dust handling system, incl. a new bag filter plant, was built. As part of these changes improvements to plant and subsystems were implemented to improve plant availability and equipment stability. Objectives: prove the capability of the HIsarna ironmaking technology to achieve at least 35% reduction in CO_2 emission intensity, compared to blast furnace operated site based on Best Available Technology Currently Installed (BAT). Meaningful outcomes: The trials with biomass and scrap demonstrated that a CO_2 reduction of min. 50% can be achieved with the HIsarna process, without using a Carbon Capture technology. In addition, the trials replacing the conveying gas with CO_2 demonstrated that it was possible to produce a Carbon Capture ready process gas. These two factors combined show that the HIsarna technology has a major role to play in reducing the C footprint of the steel industry.

STEPWISE (STEPWISE, H2020; 1/05/2015-30/04/2019) "SEWGS Technology Platform for cost effective CO_2 reduction the in the Iron and Steel Industry" is a solid sorption technology for CO_2 capture from fuel gases in combination with water-gas shift and acid gas removal. The STEPWISE project will achieve this by the construction and the operation of a pilot test installation at a BF site enabling the technology to reach TRL6 as the next step in the research, development and demonstration trajectory. Hence further reducing the risk of scaling up the technology. Objectives:

- Higher carbon capture rate – i.e. lower carbon intensity, 85% reduction
- Higher energy efficiency – i.e. lower energy consumption for capture (SPECCA), 60% reduction
- Better economy – i.e. lower cost of CO_2 avoided, 25% reduction

Meaningful outcomes: The HT-PSA CO_2 adsorbent was shown to separate CO_2 – H_2 with the targeted single-column efficiency of >90% CO_2 removal, >90% CO_2 product purity at <1 mol steam per mol CO_2 removed. Simultaneous deep desulphurization of the H_2 product was demonstrated. The sorbent was produced using industrial procedures and equipment, surpassing the targeted production rate of over 10 tonne/day.

C2FUEL (C2FUEL, H2020; 1/06/2019–30/11/2023) "Carbon Captured Fuel and Energy Carriers for an Intensified Steel Off-Gases based Electricity Generation in a Smarter Industrial Ecosystem". The project is based on the development of CO_2 conversion technologies for the displacement of fossils fuels emission according to the IS concept among carbon intensive industries, power production, and local economy. This concept will be carried out at Dunkirk including DK6 combined cycle power plant, Arcelor Mittal steel factory and one of the major European harbor. Objectives: The C2FUEL project aims to develop energy-efficient, economically competitive and environmentally friendly CO_2 conversion technologies. In particular, the CO_2 present in the BF gas will be selectively removed and combined with green hydrogen produced by electrolysis in order to produce two energy carriers (dimethyl ether and formic acid). This process, allowing the reuse of CO_2 emitted from the BF, through a circular approach aims at mitigating up to 2.4 Mt of CO_2 per year. Results: Major results have been achieved during the first 16 months of the project for each unitary brick to be included in the final demonstration pilot. In particular, the design of the CO_2 capture unit is on-going; solid oxide electrolysis cells and stacks have been manufactured for exhaustive characterization; first membranes for DME production have been manufactured and characterized and a catalyst screening is underway; a catalyst screening have been performed for CO_2 electroreduction into formic acid. Formic acid will be used in a dedicated genset to be installed within Dunkirk Harbor for clean electricity generation and DME will be tested on a real internal combustion engines to assess its potential as a fuel for heavy-duty mobility.

MORSE (MORSE, H2020; 1/10/2017–28/02/2022) "Model-based optimisation for efficient use of resources and energy" project aims to improve the products, business operations, competitiveness, and the energy and raw material efficiency of the European steel industry. Software houses, researchers developing models and steel factories worked together to develop software tools for reforming, accelerating and managing heavy production processes. Objectives: the main project's objective is to develop more advanced tools in order to improve the quality of steel as well as the management of complex processes. In particular, it aims at finding new ways for managing the entire production chain, lowering the energy and raw material consumptions as well as reducing yield losses and increasing the high quality and production rates. Especially model-based software tools are being tested in close cooperation with various European steel mills. Results: Integration of developed models and optimisation solutions to unit and through-process applications, including predictive raw material and energy optimisation tools for the whole process route. Integration and validation stages, with iterative improvements in close collaboration with industrial partners, have led to increase yield and product quality of high-strength carbon steels, stainless steels and cast steels.

CESAREF (CESAREF, Horizon.1.2-Marie Skłodowska-Curie Actions (MSCA); 01/10/2022-30/09/2026). Refractory materials are an essential part of high-temperature industries including iron and steelmaking. They are made specifically to endure severe stress from production processes as well as various combinations of thermos-mechano-chemical damage mechanisms. Yet, the onset of a European move to net-zero emissions and digitalised processes is pushing them to adapt. Objectives: the EU-funded CESAREF project, led by a team of steel, refractory and raw material producers and specialists, aims to make this a comfortable transition. To do this they will study and implement methods to improve energy efficiency and durability, efficiently utilise raw materials and enforce improved recycling, research microstructure designs for improved sustainability and prepare for the arrival of hydrogen steelmaking. Meaningful outcomes: a consorted and coordinated European network with steel, refractory, raw material producers and key academic poles will tackle the following key topics: Efficient use of raw materials and recycling; Microstructure design for increased sustainability; Anticipation of hydrogen steelmaking; Energy efficiency and durability. While creating new developments in the I&S and refractory industries, the network will train highly skilled doctoral candidates capable of communicating and disseminating their acquired knowledge. CESAREF will create a core team across the European refractory value chain, accelerating the drive towards the European refractory industries push towards sustainable materials and processes, as well as Net-Zero emission Steel production. This will help to create and secure sustainable employment in the European refractory and I&S industries.

GreenHeatEAF (GreenHeatEAF, Horizon.2.4-Digital, Industry and Space; 01/01/2023-30/06/2026). EAF steelmaking is the key technology for decarbonised steelmaking, either in scrap-based plant by modification of existing processes for further decarbonisation, or as new EAF installations in decarbonised integrated steel works to (partly) replace the classical BF-BOF production. At same time the EAF is the most important example for modular and hybrid heating, already now combining electric arc heating with burner technologies. Consequently, it was selected as main focus of GreenHeatEAF for the Call „Modular and hybrid heating technologies in steel production". Objectives: GreenHeatEAF develops and demonstrates the most important decarbonisation approaches at EAFs including the use of hydrogen to replace natural gas combustion in existing or re-vamped burners or innovative technologies like CoJet. Furthermore, decarbonisation of EAF steelmaking by solid materials like DRI/HBI and renewable carbon sources like biochar is tackled. Technologies to re-optimise the heating management with maximum heat recovery of off-gas and slag employing new sensor and soft-sensor concepts as well as extended digital twins are developed: as result the extended CFD and flowsheeting models, and monitoring and control tools will prognose the influences of the different decarbonisation measures on EAF and process chain to support upcoming decarbonisation investments and to enable the control of decarbonised hybrid heating with maximum energy efficiency. GreenHeatEAF combines trials in demonstration scale, e.g. in combustion- and EAF-demo plants, with validations in industrial scale and digital optimisations with high synergy. Thus, it completely follows the Horizon Twin Transition and Clean Steel Partnership objectives and the target to progress decarbonisation technologies from TRL 5 to 7. This synergic concept of GreenHeatEAF supports implementation and digitisation to speed up the transition of the European steel industry to highly competitive energy-efficient decarbonised steel production.

H2STEEL (H2STEEL, Horizon.3.1-The European Innovation Council (EIC); 01/10/2022-30/09/2025). Steel mills and metallurgical plants pose a significant challenge to reaching net-zero carbon emissions. The EU-funded H2STEEL project hopes to offer a solution by converting biowaste and biomethane into green hydrogen, carbon, and critical raw materials through a new type of catalysed pyrolysis. Using a newly designed reactor employing a novel catalyst, biomethane can be converted to green hydrogen in a low-cost way. Derived materials can then be used in steelmaking processes. This innovative solution avoids the release of CO_2 and results in a net reduction of greenhouse gases. Objectives: H2STEEL project proposes an innovative, disruptive solution to convert wet waste streams into green Hydrogen, Carbon and Critical Raw Materials. The proposed innovative solution aims at supporting the green transition of one of the most hard-to-abate industrial sector: metallurgy. In particular, H2STEEL combines the conversion of biowaste and bioCH4 through innovative catalyzed pyrolysis with chemical leaching, to fully convert biowastes into Green Hydrogen, Green Carbon (biocoal), and recovery of Critical (inorganic) Raw Materials. Biomethane pyrolysis is carried out in a brand new, ad-hoc designed, and proof-of-concept reactor, on a bed of biocoal made from pre-carbonized biowastes: this will enhance the efficiency of the methane cracking step to generate Green Hydrogen. As new solid carbon from methane cracking is generated on the biocoal surface, thus reducing the performance of the catalyst, new biocoal-catalyst is inserted in the reactor, while the spent biocoal is removed: the continuous renewal of the catalyst is feasible thanks to its low cost, and to the market value of the spent catalyst. This material, fully bio-carbon based, is then used in steelmaking as a substitute of metallurgical (fossil) coke, generating a net GHG reduction, EU ETS (Emission Trading Scheme) compliant. The regeneration of the spent catalyst thus becomes unnecessary, as the biocoal is used in a downstream process, avoiding the release of CO_2 in atmosphere (as it happens in the SMR process or in most of the catalysts regeneration steps). Meaningful outcomes: as part of the H2STEEL project, the final design of the POC is almost complete after the first year, so that the block flow diagram of all the different sections is available, and the procurement of equipment, sensors and control units as well as the on-site testing of individual units already supplied are underway. Due to the use of biowaste, the identification of suitable streams has been carried out as well, and four typologies of biobased streams have been selected based on the annual production volumes, the chemical composition, the disposal cost, the availability, and inorganic compound content. In addition, during the first year of the project, based on the results obtained from the characterization of the waste streams, biochars were produced and upgraded at lab scale, for the identification of the optimal process parameters. In parallel, preliminary laboratory-scale methane pyrolysis tests were carried out to determine the best operating conditions for the conversion of biomethane into hydrogen. Laboratory kinetic tests were also carried out to obtain complementary information useful for predicting POC performances under different conditions. Finally, preliminary available energy and mass balances, enable the energy modelling of the proposed H2STEEL system.

ModHEATech (ModHEATech, Horizon.2.4-Digital, Industry and Space; 01/03/2023-28/02/2026) project aims to decarbonise industrial heating by introducing hybrid technology that combines electrification and gas burning. This solution combines different technologies through ‘hybrid heating’ to improve efficiency. It uses off-gases from the furnace to recover enthalpy and partially electrifies the furnace with an induction system. The electricity needed to power the inductor will be provided by a renewable energy source (RES) and a heat recovery system. Objectives: the main objective is to decarbonize this process, based on the introduction of hybrid heating technology, based on electrification and gas-burning properly combined. This solution provides an opportunity to explore the synergic effect of different technologies, by “hybrid heating”. Moreover, the whole efficiency of the heating process can be furtherly improved by the recovery of enthalpy content of off-gases from the furnace. The furnace partial electrification will be realized by the installation of an induction system. The electricity to feed the inductor will be provided by a renewable source (RES) and by the heat recovery system.

ReMFra (ReMFra, Horizon.2.4-Digital, Industry and Space; 01/12/2022-31/05/2026) will develop a process that will allow the valorisation of steelmaking residues, which will be tested and validated in an industrial-scale demonstration plant. Objectives: the ReMFra process will allow to valorise steelmaking residues, such as filter dust, scale, sludge and slags, to obtain pig iron, iron rich oxides, a highly concentrated zinc oxide and an inert slag. ReMFra comprises two main parts to be developed, improved and tested at industrial scale: Plasma Reactor and RecoDust. The first will be dedicated to recover the coarse residues (scale, sludge, slag), while the second will focus on fine-grained dusts. The project will allow the improvement of iron yield using recovered pig iron instead of new pig iron and replacing the iron ore with the iron rich oxide. The recovery of concentrated ZnO and inert slag as by-products will provide a significant source of income and will contribute to the overall carbon neutrality. To reach the full circularity, the process foresees the use, as reducing agent, of secondary carbon sources (i.e. waste plastics). Energy recovery solutions will also be integrated in the metal recovery process starting from enabling the use of molten pig iron.

Dust2Value (Dust2Value, Horizon-CL4-2023-TWIN-TRANSITION-01; 01/01/2024-31/12/2026) project aims at integrating digitalization and machine learning techniques for process modelling and optimization. The project will leverage machine learning algorithms trained on kinetic data from thermogravimetry to create an accurate and comprehensive process model. This model will be used for the dimensioning of the prototype and will be further developed into a digital twin, providing a real-time representation of the physical process. The digital twin will enable continuous monitoring, analysis, and optimization of the process, ensuring optimal performance, and facilitating the rapid implementation of improvements. This advanced approach to process modelling will significantly enhance the Dust2Value process optimisation, driving innovation in the field of steelmaking residue recycling. Objectives: the Dust2Value project aims to transform the steelmaking residue recycling process by introducing an innovative hydrogen reduction technology that efficiently recovers valuable metals, such as zinc and iron, from steelmaking residue streams. This environmentally-friendly technology supports the circular economy, reduces greenhouse gas emissions, and contributes to a sustainable future for the steel industry. The Dust2value process utilizes green hydrogen to reduce zinc oxide and iron oxide present in the residue, converting them into gaseous zinc that evaporates, re-oxidizes with water vapor to fine-dispersed ZnO particles which leave the furnace via the off-gas system and are recovered in bag house filters. Additionally, a secondary DRI is produced. The novel design of the Dust2Value process recovers heat and hydrogen generated during the re-oxidation of gaseous zinc to fine-dispersed ZnO particles, optimizing its energy efficiency. The project will design, construct and optimize a prototype rotary kiln that enables optimized heat transfer and gas-solid interactions, ensuring effective metal recovery.

H2PlasmaRed (H2PlasmaRed, Horizon-CL4-2023-Twin-Transition-01; 01/01/2024-31/12/2027) project aims to develop hydrogen plasma smelting reduction (HPSR) technology for the reduction of iron ores and steelmaking sidestreams to meet the targets of the European Green Deal for reducing CO_2 emissions and supporting the circular economy in the steel industry across Europe. Objectives: the H2PlasmaRed's ambition is to introduce a near CO_2-free reduction process to support the goal of the Paris Agreement - a 90% reduction in the carbon intensity of steel production by 2050. To achieve this, H2PlasmaRed will develop HPSR from TRL5 to TRL7 by demonstrating the HPSR in a pilot-HPSR reactor (hundred-kilogram-scale) that is an integrated part of a steel plant, and in a pilot-scale DC electric arc furnace (5-ton scale) by retrofitting the existing furnace. The project's end goal is to establish a way to upscale the process from pilot-scale into industrial practice. To support this goal, the novel sensors and models developed and implemented in the project are used for HPSR process optimization from a reduction, resource, and energy efficiency standpoint.

MaxH2DR (MaxH2DR, Horizon-CL4-2021-Twin-Transition-01-18; 01/06/2022-31/05/2026). H_2-enriched direct reduction (DR) is the key decarbonisation technology for integrated steelworks mentioned in pathways of all major steel producers. Natural gas driven DR is established in industry mostly outside Europe but there are no experiences with high H_2 enrichment > 80%. H_2 based reduction is no principal issue but endothermic and the influences on morphology, diffusion and effective kinetics are not known. Also properties and movement of particles in the reactor are not know and issues like sticking cannot be excluded. Probably, temperature distribution and flow of solids and gas will be clearly different. No reliable prognosis is possible yet, in particular with regard to local permeability, process stability and product quality of industrial size furnaces with higher loads on the particles and larger local differences. Many activities are initiated for first industrial demonstration of H_2-enriched DR but they will not close many of these knowledge gaps. Objectives: MaxH2DR provides missing knowledge and data of reduction processes. A world-first test rig determines pellet properties at conditions of industrial H_2 enriched DR furnaces and a physical demonstrator shows the linked solid and gas flow in shaft furnaces. This will be combined with digitals models including the key technology DEM-CFD to provide a hybrid demonstrator able to investigate scale-up and to optimise DR furnace design and operating point. This sound basis will be used to optimise the process integration into existing process chains. Simulation tools will be combined to a toolkits that covers impacts of product properties on downstream processes as well as impacts on gas and energy cycles. Thus, promising process chains, sustainable and flexible, will be achieved for different steps along the road to decarbonisation. The digital toolkits will support industrial demonstration and implementation and strengthen digitisation and competitiveness of the European steel industry.

ALCHIMIA (ALCHIMIA, Horizon.2.4-Digital, Industry and Space; 01/09/2022-31/08/2025) project will create a federated learning and continual learning-based platform to support major European metallurgy industries in fully adopting AI and the transition to green manufacturing processes. The project will therefore address the challenges of the steel sector by creating an innovative system that automates and optimises the production process. Objectives: ALCHIMIA aims to build a platform based on Federated Learning and Continual Learning to help big European metallurgy industries unlock the full potential of AI to support the needed transformations to create high-quality, competitive, efficient and green manufacturing processes. The project will address the challenges of the steel sector, creating an innovative system that automates and optimises the production process dynamically with a holistic approach that includes scrap recycling and steelmaking. ALCHIMIA will find an optimal mix to reduce energy consumption, emissions and waste generation of steelmaking while guaranteeing to obtain high-quality products. The replicability and scalability of ALCHIMIA will be enabled through a complementary use case for the manufacturing of automotive parts. The developed system will be used for prognostic optimisation of the mix of input materials charged in the furnaces to obtain a certain product quality that matches the customers' specifications while reducing the environmental impact and the energy consumption. ALCHIMIA will not only seek the optimal mix for the charge of metallurgy furnace, it will also determine the best combination of learning capacities to enable a smooth green transition for all industries thanks to unprecedented collaboration.

5.2 Chemical Sector

To promptly respond to the energy crisis and its detrimental impact on the chemical industry's competitiveness there is an urgent need for action to safeguard the European chemical sector. This entails protecting high-skilled quality jobs in Europe while simultaneously striving towards climate neutrality and fostering an internationally competitive chemical industry. In this regard, the main requests from the EU social partners of the chemical industry includes (ECEG & industriAll Europe, 2023):

- Ensuring fully adherence to social dialogue at all levels, in line with national or European legislation.
- Urging companies to continue investing in both infrastructure and workforce development, while calling on public authorities to expedite support for industrial decarbonisation projects and related energy infrastructure by streamlining authorization processes.
- Implementing energy efficiency inititaives alongside investments in renewable and low-carbon energy sources to reduce reliance on fossil fuels.
- Utilising all available resources to provide financial relief to stuggling industries, potentially through mechanism akin to SURE inititiave or remaining funds from the NEXT Generation EU recovery package, with social conditionality attached.
- Facilitaiting access to financing mechanisms, especially for SMEs, to prevent further disruption of industrial value chains in Europe.
- Developing the Green Deal Industrial Plan to steward the European industry through the current challenging times.

In addition, the project titled "On the Road to Climate Neutrality 2050 – the Role of Social Partners in the Decarbonisation of the Chemical, Pharmaceutical, Rubber and Plastics Industries", carried out by the European social partners of the chemical sector, industriAll European Trade Union and the European Chemical Employers' Group (ECEG) (Schöneberg, Homann, Ballaire, & Kessaria, 2023), summarises the comprehensive findings of the project, including a literature review and insights gleaned from 23 interviews with experts representing European and national social partner organisations, as well as company representatives from 7 countries. These findings served as the foundation for the development of the research report, which in turn informed the creation of the project toolbox and guided the proceedings of three interactive workshops and the final conference. The report delves into the framework conditions necessary for achieving a successful transition to climate neutrality by 2050, while also delineating the role of social partners and social dialogue in this context. The report is also complemented by the project toolbox designed to supports national social partners in navigating their roles in this field.

5.2.1 Projects on Energy Efficiency involving the Chemical sector

CatASus (CatASus, H2020; 01/05/2016-30/04/2023) “Cleave and couple: Fully sustainable catalytic conversion of renewable resources to amines”. The problem addressed is the fully sustainable conversion of renewable resources to bio-based chemicals for future manufacturing of polymers, drugs, materials. Lignocellulose is produced in large (~160MT/year) quantities as part of agricultural and forestry waste, (not competing with food), but currently it is not valorized because of its challenging structure. This proposal aims to tackle this. Two fundamental challenges addressed: 1. efficient depolymerization of lignocellulose to platform chemicals (also lignin) and the conversion of these platform chemicals into useful compounds, primarily amines. Amines are ubiquitous in the chemical industry, they are highly demanded in medicinal, polymer chemistry or as fine chemical intermediates. In this proposal the sustainable production of amines is foreseen. The aim of this research program will deliver groundbreaking approaches in catalysis that are necessary to establish an entirely new lignin valorization platform. Objectives: Enable chemical pathways for the production of amines through alcohols from renewable resources, preferably lignocellulose waste. Meaningful outcomes: Stabilization of reactive C2-aldehydes as acetals or by tandem catalysis. The acetals provide valuable novel lignin derived platform. The CuPMO catalysed reductive fractionation of lignocellulose to obtain 4-propanol guaiacol in high selectivity. Integrated catalyst recycling via catalytic conversion of all process residues in supercritical methanol to aliphatic alcohols. The intermediate alcohols are ideally set up for further C-C or C-N bond formation to get valuable products. The project developed concrete valorization pathways from the aromatics and aliphatics obtained. Cellulose derived aliphatics to jet fuels/ Lignin derived aromatics to valuable amines (pharma and polymer building blocks).

On the Road to Climate Neutrality 2050 (On the Road to Climate Neutrality 2050, Social Dialogue; 02/2021-05/2023). The project focused on developing scenarios related to technological pathways and their impact on companies and workers in the decarbonisation efforts of the chemical, pharmaceutical, plastics and rubber sectors. In this context, it also identified main topics for social partners, and devised tools and recommendations to facilitate social dialogue within this framework. Objectives: To identify main topics for social partners in the decarbonisation process; To elevate the level of trust between social partners and enhance the quality of social dialogue through collaborative development of scenarios and solutions.

5.2.2 State of the art of the Energy efficiency in the "Consumer Goods Companies".

In the consumer Goods European Industries, since the 1970s, more efficient energy use has weakened or eliminated the link between economic growth and energy use. At the global level just 37 percent of primary energy of this type of industries is converted to useful energy—meaning that nearly two-thirds is lost (Jochem, 2015). The next 20 years will likely see energy efficiency gains of 25–35 percent in most industrialised countries and more than 40 percent in transition economies. Thus energy efficiency is one of the main technological drivers of sustainable development world-wide. Energy policy has traditionally underestimated the benefits of consumer Goods energy efficiency, for society, the environment, and employment. Achievable levels of energy efficiency depend on a country's industrialisation, motorization, electrification, human capital, and policies. But their realisation can be slowed by sector- and technology-specific obstacles—including lack of knowledge, legal and administrative obstacles, and the market power consumer Goods industries. Governments and companies should recognise innovations that can lower these obstacles. The external costs of energy use can be covered by energy taxes, environmental legislation, and greenhouse gas emissions trading. There is also an important role for international harmonisation of regulations for efficiency of traded products. Rapid growth in demand provides especially favourable conditions for innovations in developing countries—enabling these countries to leapfrog stages of development if market reforms are also in place. The economic potentials of more consumer Goods efficient energy use will continue to grow with new technologies and with cost reductions resulting from economies of scale and learning effects. Considerations of the second law of thermodynamics at all levels of energy conversion and technological improvements at the level of useful energy suggest further potential for technical efficiency of almost one order of magnitude that may become available during this century. Finally, structural changes in industrialised and transition economies—moving to less consumer Goods energy production and consumption—will likely contribute to stagnant or lower energy demand per capita in these countries.

There are particular European programs that aims at energy efficiency, and, given their importance, a lot is centred on the consumer goods industries. this program is the Intelligent Energy Europe Program (IIE) (EC, 2020), established with Decision no. 1639/2006 / EC, included among its objectives to promote energy efficiency, renewable energy sources and energy diversification, has contributed to ensuring safe and sustainable energy for Europe by supporting the EU states committed to achieve the objectives of the European 2020 strategy (-20% greenhouse gas emissions; + 20% energy efficiency; + 20% renewable energy), strengthening competitiveness through measures aimed at encourage energy efficiency and the rational use of energy resources (SAVE sub-program, Specific Actions for Vigorous Energy Efficiency) with particular focus on Consumer goods companies.

An example of this application is the following projects:

(LEAP4SME, 2020) Linking Energy Audit Policies to enhance and support SMEs towards energy efficiency. The proposed project intends to support Member States in establishing or improving national and local schemes for SMEs to undergo energy audits and implement cost-effective recommended energy-saving measures.

An initial work of policies and programmes mapping will be followed by an in-depth understanding of their strengths and weaknesses, with the aim of overcoming the current criticalities and bottlenecks. At the same time a work of characterisation of SMEs in terms of energy consumption, size and sector will be carried out to understand effective ways to properly address existing and innovative energy audit policies.

Provided a continuous interaction (by means of workshops, questionnaires, meetings) with policy makers as well as SMEs and ESCOs/Energy Auditors associations, a set of policy proposals and recommendations will be then developed and diffused.

The priorities guiding the policy and recommendation development will be:

- Effectiveness and orientation to real market needs;

- Integration with other points of the EED, particularly article 7 Energy Efficiency Obligation Schemes and alternative measures;

- Replicability, at least for SMEs sector/size/region;

A fundamental part of the project, with a relevant participation requested to each partner, will be a continuous action of capacity building and dissemination addressed to policy makers and relevant stakeholders at European, National and Regional level.

In order to concentrate the efforts on new challenges and to valorise previous efforts, the Consortium is committed to take as much advantage as possible of results obtained in previous pertinent EU funded projects (such as ENSPOL, ODYSSEE-MURE, EPATEE) and relevant initiatives such as EEFIG and its related Sustainable Energy Investment Forums.

On request of the European Institutions, the Consortium would also be very glad to contribute, through findings and results of the project, to the current debate on the SME definition

ODYSSEE and MURE Project (info(at)odyssee-mure.eu, 2001-2010)

The general objective of the project is to provide a comprehensive monitoring of energy consumption and efficiency trends as well as an evaluation of energy efficiency policy measures by sector for EU countries, by:

- Evaluate and compare energy efficiency progress by sector, and relate this progress to the observed trends in energy consumption.
- Contribute to the evaluation of national energy efficiency policy measures and analyse their dynamics of implementation.
- To provide results in an interactive and attractive way to decision makers and actors involved in energy efficiency, the project has developed specific data and policy tools.

The originality of the project is to cover all sectors and end-uses. The approach is homogeneous and harmonised and aims to provide an overall picture of the trends and measures by sector. With the new “Policies by Topic” tool, the MURE database provides a tool to get a quick overview of policies specifically addressing target groups as e.g. Consumer goods Companies, with special attention to the SME of this category.

The number of measures addressing SMEs differs a lot between the countries. Whereas in Germany, the Netherlands or Norway there are a lot of measures addressing SMEs, in some other countries, such as Austria, Cyprus, Czech Republic, Greece or Romania SMEs are only targeted with very few or no measure

Policy measures in MURE specifically targeting SMEs can be categorized in two broad classes: i. Financial Measures: Majority of the measures related to SMEs fall in this category. It includes measures dealing with funds, loans, subsidies, financial support schemes,consulations, financial incentives and aids for SMEs. Several measures provide financial support in the form of subsidies, loans and aid for Energy audits in SMEs. Such measures have been reported by Austria, Croatia, France and Spain. These measures provide technical and financial support to conduct comprehensive energy audits within SMEs.Measures related to energy-related advice and consulation have been reported by Germany, Austria, Spain and Malta. ii. Information/Educational/Training Measures: These measures encompass education and training activities for SMEs on how to enhance energy efficiency, resource planning and management and the behavorial-training of the employees of the enterprise towards more responsible energy-related actions. Such measures have been reported by Finland and Ireland. UK reports a "Smart Metering" measure for the SMEs. The UK Department of Energy and Climate Change (DECC) is leading a roll-out (links below) of smart meters with support from the industry regulator, Ofgem. DECC estimates that over the next 20 years the installation of smart meters will provide £6.7 billion net benefits to the UK: the programme will cost £12.1 billion and provide £18.6 billion in benefits. Since 2009, where suppliers have replaced or newly installed a meter at a medium-sized non-domestic site, that meter has had to be an advanced meter. Since April 2014, all supplies to these sites have to be provided through advanced meters. The policies targeting SMEs are listed below under the above mentioned two categories. Energy Efficiency Trends and Policies in Industry: Policy measures specifically tailored for SMEs Information/Education/Training Financial Austria SME-Energy Cheque Croatia Energy audits of SMEs Finland Energy Advice to SMEs France Loans for SMEs Germany: a. Special fund for energy efficiency in SMEs; b. KfW Energy consultations for SMEs; c. Promotion of energy efficient crosscutting technologies in SMEs Ireland SME Energy Efficiency Malta Support schems for Industry and SMEs Poland Energy efficiency investments in SMEs Slovenia Financial incentives for investment in energy efficiency and renewable in SMEs Spain; a. IDEA-ERDF Programme for SMEs b. Aids to SMEs and large companies in the industrial sector Sweden Energy efficiency in SMEs Source: MURE database,

June 2015 Philips - Pay per Lux (Lisa Goldapple, 2016)

With its 'Pay per Lux' service, Philips is shifting from a one-time sale to a lifetime service model. The company offers customers a full long-term lighting service for offices including electricity. The idea is a cradle-to-cradle rental scheme whereby Philips retains responsibility for the performance of the lighting over a 15-year period and customers pay for the energy consumed through a quarterly fee. The solution encompasses a total service and warranty solution that fits within the 15-year timescale of the contract. Any replacements during the life of the contract will make use of the latest LED lighting technologies. This service aims to create energy and carbon savings compared to traditional office lighting installations.

5.3 The Refining Sector

5.3.1 State of the art of the Energy Efficiency in the refining industry

Complex refineries can improve energy efficiency in a number of ways: increased heat interchange between process streams; thermal exchange within and between process units and hotter charge feed between units; use of more efficient heaters or furnace processes; gas turbines with pre-heated air and waste heat steam generation (when feasible); etc. The optimization of a complex refining can result in fuel consumption energy savings of between 10%-15%. The energy efficiency of refineries has increased over the years, stimulated by economic events such as increases in the cost of fuel consumed in refineries. On the other hand, the corresponding efficiency has increased with the price of fuel. Research carried out by American Petroleum Institute (API) concluded that this reduction in energy use was due to investments made in new plants, operational improvements and the modernization of old equipment.

The actual specific consumption levels (the ratio between the energy consumed by the refinery and the tonnes of feedstock processed) of a sample of European refineries in recent years are ranging from 1.5 GJ/t to 4.0 GJ/t of crude, with an average of 2.75 GJ/t. Around 3 – 9 % of the crude feedstock received is burnt in the refinery.

Examples of energy efficiency of refinery industry

- Chinese-European Emission-Reducing Solutions (CHEERS, Project reference: 764697 - 01/10/2017 to 30/09/2022). This H2020 project will provide an efficient route for carbon capture from the refinery industry. In addition, the system will use petroleum coke as a fuel with hardly any emissions of sulphur and heavy metals. For other industries, the CLC-CCS technology could provide an economical way of capturing combustion-related carbon emissions with an exceedingly low efficiency penalty.
- Scenarios for integration of bio-liquids in existing REFINERY processes (4REFINERY, Project reference: 727531, 01/05/2017 to 30/04/2021) – Period 01/05/2017 to 30/04/2021. The concept is based on innovative technologies for biomass conversion, including ablative fast pyrolysis (i.e. convective melting) and mild catalytic hydrotreating, while incorporating state-of-the-art renewable H2-production technology as well as optimal energy integration.
- Compact Gasification and Synthesis process for Transport Fuels (COMSYN, Project reference: 727476; 01/05/2017 to 30/04/2021) – Period 01/05/2017 to 30/04/2021. In this H2020 project the Fischer Tropsch (FT) products will be refined to high quality drop-in liquid transport fuels at existing oil refineries. The novel gasification technology will enable the use of wider feedstock basis than the current gasification processes. In addition to woody residues, the process is able to use straw and other agricultural residues, and various waste-derived materials. The produced FT-wax will be transported to existing large scale oil refinery, which will be gradually converted into biofuel refinery as the number of primary conversion plants increases.
- CarbON Valorisation in Energy-efficient Green fuels (CONVERGE, Project reference: 818135, 01/11/2018 to 30/04/2022) – Period: 01/11/2018 to 30/04/2022 . The CONVERGE project validates an innovative value chain for the production of sustainable biodiesel. The innovative configuration reduces the total number of unit operations needed to achieve the conversion of secondary biomass and waste streams into biodiesel, while at the same time producing additional intermediate green refinery products.

5.4 Non-ferrous metals Sector

5.4.1 State of the art of the Energy efficiency in in the non-ferrous metals sector.

The production of primary aluminium requires 14-16 MWh/t of electrical energy, accounting about 85% of the total energy consumption. Secondary aluminium requires 0.12-0.34 MWh/t of electrical energy. Copper (total energy 3.3 MWh/t, electrical energy 1.5 MWh/t), zinc (total energy 14 MWh/t, 1 MWh/t electrical energy) and other metals requires less total specific energy, but also consume more fossil fuels, and more specific CO2 emissions (IES, 2018).

In Europe, the total energy use in 2017 by the non-ferrous metals industry was 432 Petajoule (PJ, corresponding to 120 TWh). Electricity is by far the most important energy carrier with a share of 58% of final energy use (69 TWh) in 2017 (IES, 2018). The non-ferrous metal industry is the sector with the highest share of electrical energy.

Figure 5.1 shows the relative share of energy sources of main energy Intensive Industry (IES, 2018).

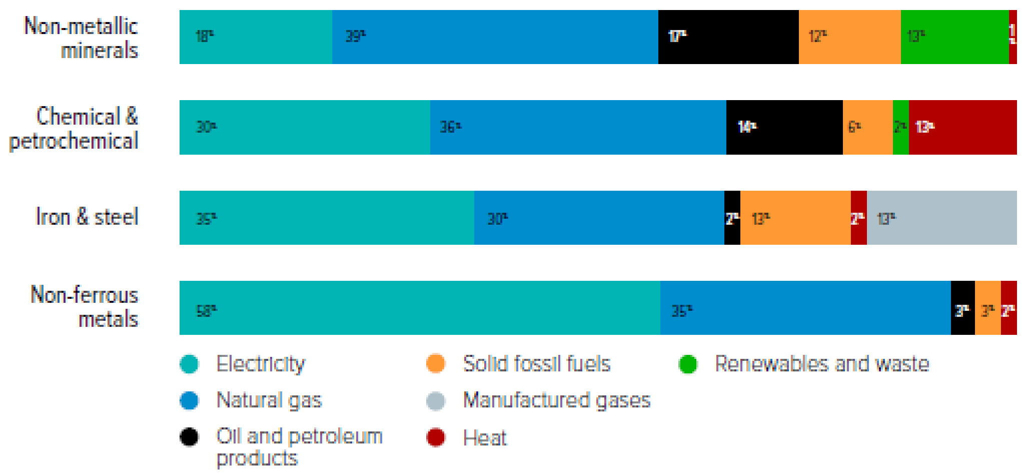

Figure 5.1: Relative shares of energy carriers in the final energy use of select energy intensive industries in 2017 (IES, 2018).

In the last 30 years a significant reduction of CO_2, and more in general Green House Gas (GHG) emissions, has been obtained. Between 1990 and 2015, the non-ferrous metals industry reduced its CO2 equivalent emissions (direct and indirect) of about 61% (IES, 2018). A strong reduction of GHG emission is due to the drastic reduction of emissions of perfluorocarbon (PFC), which are gases at high greenhouse effect, produced (mainly) in the primary aluminium production process.

In the year the aluminum industry made a big effort to reduce these emissions, by means of process improvement, implementation of monitoring and control system training of personnel.

In the same period the reduction of energy consumption contributes to the reduction of CO2 emission.

The technical evolution of the sector, from 1990 to now, has led to a significant reduction of the energy consumption of around 15%. A further improvement, favoring both energy efficiency and decarbonization has been the shift of the type of fuels: the use of solid fuels and oil decreased from 11% and 12%, respectively, in 1990, down to 3% in 2017, replaced by natural gas and electrical energy, contributing to increase energy efficiency and to the reduction of CO2 emission.

Improvement have been also due to the introduction of new plants, new operating procedures, larger number of sensors, control systems and higher automation.

A recent study, involving Non-ferrous materials and Carbon nanomaterials, was mainly focused on EE (Gabris & Ping, 2021), with the following main objectives: A nearly complete list of carbon nanomaterials-based nanogenerators was present; Four different roles of carbon nanomaterials in nanogenerators was summarized; Many kinds of nanogenerators, such as PENG, TENG, and TNG, were introduced; Mechanical, thermal, and fluid/blue energies were harvested by nanogenerators. Current challenges and future trends in this field were provided. In particular, adjusting and regulating the activity of carbon nanomaterial-based components are the most fundamental strategies to improve the overall electric output. This can be achieved by chemical modification of carbon nanomaterials and compounding them with other materials. It is also important to constantly develop more effective ways to chemically modify carbon nanomaterial and introduce more active groups and functional materials to modulate their performance. It is very essential to expand the application scope of carbon nanomaterial-based NGs and further manipulate their aspects and functional diversity. The advantages of easy fabrication, low cost, flexibility, lightweight, and biodegradability, can extend their potential applications into many fields.

In order to develop new synthesis methods for the efficient use of rare earth elements from newly discovered rare earths deposits in Turkey, Zirconia ceramics doped with different rare earth elements was obtained by a green hydrothermal method and the thermal and dielectric properties were investigated to develop thin ion conductive films (Piticescu, et al., 2021). In addition, Zirconia ceramics doped with mixed rare earth oxides was obtained by a green hydrothermal method and their ionic conductivity properties were investigated with the aim to be used as material for solid oxide fuel cells for clean energy applications (Ghiță, et al., 2024).

More recently, as nanofiltration technology significantly reduce the energy consumption in treatment of waste waters and purification of plant extracts for drugs fabrication, the digitization of membranes fabrication and reducing environmental impact of manufacturing processes were achieved (Chiriac, et al., 2022). In particular, 3D structures based on hybrid ZnO-CNT 1D nanostructured (nanorods) powder, obtained by the hydrothermal method, were investigated for 3D printing of porous structures as support for impregnation with inorganic salts. NaNO3, KNO3 and 1:1 vol% saturated solution of nitrates mixture (NaNO3:KNO3) were investigated as PCMs impregnation agents, using a solvothermal process in isostatic pressure conditions. The main novelty of this recent work consists in using a ZnO-CNT-based nanocomposite powder, prepared by an own hydrothermal method at high pressure, to obtain porous 3D printed support structures with embedding capacity of PCMs.

5.4.2 European projects on energy efficiency and decarbonization

Today the EU has some of the most efficient non-ferrous metals production in the world together with a high degree of recycling, which allow a strong secondary production (which is in nature less energy demanding and more efficient).

The consumption reduction trend in EU is expected to continue, especially because of the growth in production of secondary metal through improved recycling and recovering of metals from scrap and wastes.

A projection of the energy consumption in non-ferrous metal sector, under the hypothesis of “business as usual” indicates a progressive reduction of the total energy consumption, achieving 20% in 2050 (ICF, 2015).

This study evaluated the energy saving impact of a set of energy saving opportunities applicable to the sector.

The listed opportunities were derived by the on-going technological development, including:

- Implementation of new technological solutions for plant and process optimisation
- Integrated control system of the process steps, supported by artificial intelligence

- Flue gas monitoring system to maintain proper air-to-fuel ratio
- Measurement of the energy consumption of single units and equipment for optimization
- Preventive furnace maintenance
- Inert anodes
- High efficiency burners
- Systems for energy recovery from exhaust gas
- Low temperature waste heat recovery for power generation (e.g. using Organific Rankine Cycle)
- Digitalisation and introduction of measures to favour energy efficiency

Examples of European projects are listed below.

Process and furnace optimization and control

The aim of the **DISIRE** ((Grant agreement ID: 636834) project is to evolve the existing industrial processes by advancing the Sustainable Process Industry through an overall Resource and Energy efficiency by the technological breakthroughs and concepts of the DISIRE technological platform in the field of Industrial Process Control (IPC).

With the DISIRE project the properties of the raw materials or product flows will be dramatically integrated by their transformation in a unique inline measuring system that will extend the level of knowledge and awareness of the internal dynamics of the undergoing processes taking place during transformation or integration of raw materials in the next levels of production. In this approach, the Integrated Process Control system, instead of having external experts to tune the overall processes, based on the DISIRE concept will enable the self reconfiguration of all the production lines by the produced products itself.

The project is addressed to several industrial sectors, including non-ferrous, ferrous, chemical and steel industries that are highly connected and already affiliated with the SPIRE PPP and its objectives.

Heat recovery from exhaust gas and thermal wastes

The overall objective of **ETEKINA** (Grant agreement ID: 768772) project is to improve the energy performance of industrial processes. For this to be possible, the valorisation of waste heat by a turnkey modular Heat Pipe Based Heat Exchanger (HPHE) technology adaptable to different industry sectors will be addressed within the project and demonstrated in three industrial processes from the non-ferrous, steel and ceramic sectors in order to demonstrate:

(i) the economic feasibility of the solution, and therefore
(ii) its market potential.

The project aims at designing, developing and validating an innovative solution, the **CIRMET** (820670, H2020-EU.2.1.5.3, & 2018-2022) solution, to provide energy and resource flexibility to Energy Intensive Industries (EIIs) The CIRMET solution will be validated in an operational environment (TRL7) in an existing process plant (non-ferrous sector) while the replicability of the solution will be assessed in three additional energy intensive sectors (steel, cement and water sector). For this purpose, three new demonstrators will be build up, plus the retrofitting of existing industry process unit. The new demonstrators or modules will be: EFFIMELT furnace, a new concept of flexible and modular process unit for industrial wastes treatment, RECUWASTE heat recovery unit, for flue gas heat recovery and transformation into compressed air to re-used in the same plant, having also the possibility of storing the excess energy and AFF40 (Analytic For Factory 4.0) platform, to improve process plant competitiveness, to increase energy and resource efficiency by controlling and optimizing process units.

ENERHIGH (ENERHIGH, (Structural funds); 09/09/2016-2019,) "Innovative Methods for Enhancing High Temperature Thermal Energy Storage Properties of Phase Change Materials" project proposed innovative methods for enhancing high temperature energy storage properties of phase change materials (PCMs) using a green hydrothermal synthesis technology for micro-encapsulation of the inorganic PCM in a nanostructured ceramic zinc oxide shell, with operation temperature range for thermal energy storage up to 500^{0}C degrees. The micro-encapsulation process increases thermal stability and reduces the material degradation due to corrosion produced by the inorganic PCMs such as sodium and potassium nitrates or hydrates used. The shell material is compatible both with the PCM core and construction materials used in thermal energy storage systems. The major foreseen application is in concentrated solar power systems. New market niche has been also identified for firefight protection system. Objectives:

- The implementation of a research programme enabling to develop innovative and easily scaled-up methods for micro-encapsulation of Phase Change Materials (PCM) with melting temperature 300 – 500^{0}C for thermal energy storage;
- Develop a cycle of seminars and workshops for internal (IMNR level) and external (companies, local authorities and NGOs) training of young researchers and industrial specialists in the new encapsulation methods and their performances;
- To disseminate the project results to relevant stakeholders, in order to uptake these results after the project duration.

Results:

- 2 innovative and eco-friendly technologies for microencapsulating phase change materials (PCMs) based on inorganic salts (sodium nitrate, potassium nitrate and their solutions), in a nanostructured inorganic zinc oxide shell, for energy storage working in the temperature range 300-500^{0}C, aiming to increase storage efficiency and reduce corrosion in solar energy equipment.
- Database of thermal conductivity data for PCMs obtained with the pilot installation developed in the project.

Digitalisation and measures to favour energy efficiency in the industrial production

TOP REF (Grant agreement ID: 604140) aims to develop and validate specific indicators, methodologies and non-invasive tools devoted to the improvement of resource efficiency in energy intensive continuous industrial processes in the non-ferrous, chemical and petrochemical sectors.

TOP-REF develops and demonstrate a robust, resource-efficiency-focused and cross-sectorial methodology. This methodology will be implemented in three specific, non-invasive, real time and on-line monitoring and control tools adapted to three specific continuous energy and resource intensive processes, among which aluminium industry

The aim of the CSA **MEASURE** (Grant agreement ID: 636816) is to provide support and guidance, how to reach the H2020 SPIRE Public Private Partnership goals on reduction in fossil energy intensity, non-renewable, primary raw material intensity and greenhouse gas emissions in the most effective way. MEASURE will deliver a roadmap how to evaluate processes in a standardised, comparative way

The phases of work will include a detailed, cross-sectorial stakeholder analysis on the use of existing sustainability metrics and decision support tools for different goals, stages and data availabilities; an in-depth dialogue between the MEASURE core team and the Advisory Board during two organised workshops and as final outcome, a harmonised roadmap towards universally accepted and standardised tools for environmental, economic and social assessment in process industries over the whole value chain

EE-METAL (Grant agreement ID: 694638) aims to provide enterprises with innovative technical, commercial and financial tools in order to overcome the existing barriers that hinder the adoption of energy saving measures. EE-METAL actions are mainly targeted to Metalworking and Metal Articles (MMA) SMEs, given that this sector is the biggest manufacturing sector in Europe and it is mostly composed by SMEs.

The goal is to provide awareness, information and technical capacity barriers to identify, evaluate and implement energy efficiency actions: EE-METAL adapts and standardizes for the sector existing methods and technologies such as energy audits, the standard ISO 50.001 and the use of Energy Monitoring System

The aim of **INEVITABLE** project (Grant agreement ID: 869815) is to optimise manufacturing processes by fully digitalising monitoring technology. Real-time machining process control at shop floor can significantly improve machining efficiency and the quality of finished parts. It will also reduce resource consumption and CO2 emissions for a more competitive and sustainable metallurgic industry.

FAST- SMART (FAST-SMART, H2020; 01/04/2020–31/03/2024) "FAST and Nano-Enabled SMART Materials, Structures and Systems for Energy Harvesting". The project overall concept is centred on scaling up of novel, mass-production nano-manufacturing techniques invented by FAST-SMART partners for synthesis of nano-structured smart materials and component manufacture for energy harvesting applications to significantly improve the material quality and structural reliability (>50%~100%) and reduce overall materials and processing costs (by 30%) through shortening the process chains and improving material processing efficiency, being focused on less rare-element dependence materials as well as on new energy harvester designs considering environmental strategy, thus to bring about positive, environment-related impacts to Europe (greenhouse gas emission down by 50% and waste reduction by 50%), increased EU's market share, and to promote wider implementation of Internet of Things (IoT) and Digital Single Market (DSM) in Europe, due to introduction of the new energy harvesting products, design and manufacturing services created through the FAST-SMART's partnership. Objectives: The overall goal of the EU-funded FAST-SMART project is to apply novel manufacturing techniques on a large scale which are recently developed by project members for synthesising smart nanomaterials for energy harvesting. The development of piezoelectric (PE) and thermoelectric (TE) materials using earth-abundant elements and highly efficient synthesis/manufacturing processes is expected to enhance material-supply resilience, reduce impacts on the environment, improve processing efficiency and reduce overall material costs. Results: The main driver of the project lies in a need to meet challenges particularly for the development and applications of PE and TE materials, associated structures and systems for new-generation energy harvesters, and for dealing with energy generation, storage and uses related issues with a systematic approach, and hence, to help to meet EU's targets on the social, economic and environmental developments.

SUPREME (SUPREME, H2020; 01/09/2017-31/12/2020) “Sustainable and flexible powder metallurgy processes optimization by a holistic reduction of raw material resources and energy consumption” aims at optimizing powder metallurgy processes throughout the supply chain. It will focus on a combination of fast-growing industrial production routes and advanced ferrous and non-ferrous metals. By offering more integrated, flexible and sustainable processes for powders manufacturing and metallic parts fabrication, SUPREME enables the reduction of the raw material resources (minerals, metal powder, gas and water) losses while improving energy efficiency, production rate and CO_2 emissions, into sustainable processes and towards a circular economy. Objectives: gas and water atomization as well as ball milling for metal powder production, additive manufacturing and near-net shape technologies for end-parts fabrication. Meaningful outcomes: Regarding mineral processing, significant improvements were reached without compromising the production rate or end-product quality: 1.2% reduction of grinding energy consumption (2400 kWh reduction annually for an average plant), 89% reduction of water consumption, 9.9 kt reduction of CO_2 emissions per year for 3 concentrator plants. A huge potential for further energsavings around the world is expected. Regarding powder production, KPIs were quantified for gas atomization (GA), water atomization (WA) and high energy ball milling (HEBM). A 62% reduction of energy consumption based on the use of WA powder instead of GA powder was obtained. Regarding metal AM, a dozen times re-use of L-PBF powders, without any impact on mechanical properties and with a 95% recovery rate, was shown. Regarding the MIM process, Fe-based raw material usage was reduced by 35% thanks to use of scrap materials (sprues) and L-PBF powder. Regarding the medical use-cases studied (MBA), the overall results are: a 36% reduction of raw material yield losses; a 72% reduction in energy consumption; a 5444% increase of production rate and a 52% reduction in CO_2 emissions compared to baseline processes. Regarding the HIP process (TWI), the sub-marine part use-case demonstrated a 75% improvement of the buy-to-fly ratio and an important energy saving.

OMR (OMR, H2020; 01/04/2020-31/12/2022) “X-Ray Fluorescence, Shape recognition & Machine Learning for Efficient and Economic Recycling of Mixed Metals from Co-mingled Waste” will create a unique combination of X-Ray Fluorescence (XRF), shape recognition and Machine Learning (ML) techniques to enable efficient and economic recycling of mixed non-ferrous metals from co-mingled waste. This will turn a low value feedstock into several high value output streams which will further increase the advantages of co-mingled collection and allow it to be rapidly rolled out across the EU to help meet the EU’s ambitious 65% recycling target. Furthermore the project will deliver a sustainable market for mixed metals, provide aerospace and automotive manufacturers with a new source of guaranteed quality non-ferrous metals, divert material from landfill, preserve natural resources, increase recycling rates and create employment opportunities as new facilities are rolled out across the EU. Objectives: 1. Optimise the prototype design to enable full scale sorting operations; 2. Assembly of the prototype OMR process on site; 3. Software programs developed and outputs quality tested; 4. Identify and address any product purity, software or flow issues that arise; 5. Deliver equipment use and maintenance training for all staff; 6. Wide dissemination of project results achieved within recycling and metals industries; 7. Generate sufficient interest and user willingness to pay/adopt; 8. Achieve market penetration; 9. Reach projected market volumes and geographic target markets; 10. Achieve/exceed forecast company growth. Meaningful outcomes: combination of technologies and Machine Learning (ML) techniques to enable efficient and economic recycling of mixed metals from comingled. waste. This will enable wide scale rolling out of simple, easy recycling solutions and so increase recycling rates across the EU.

NYMPH (NYMPH, H2020-ERANEt-MANUNET; 01/12/2020-30/11/2022) project addresses the topic "Manufacturing technologies for environmental and energy applications". The project starts from TRL 3 and will develop up to TRL 5 two types of membranes, one nanofiltration inorganic membrane developed at IMNR by hydrothermal functionalization of commercial CNTs with ZnO nanoparticles followed by extrusion and the second polymeric one, at SINTEF, by antifouling surface modification of commercial membranes, via UV and chemical grafting hydrophilization treatment. The novel membranes will be used for water treatment, having excellent antifouling properties and separation performances (50% reduction flux decline in time and >20% increase in permeability) and separation and purification of plant extracts (polyphenols), increasing the separation efficiency (>20% reduction flux decline in time and >20% increase in permeability). Objectives: the objective of NYMPH is to develop two novel membranes adapted to water treatment having excellent antifouling properties (50% reduction flux decline in time and >20% increase in permeability) and high separation performance (>20% increase in permeability) and separation and purification of phenolic compounds from natural plant extracts, increasing the separation efficiency (>20% reduction flux decline in time and >20% increase in permeability) compared to the state-of-the-art membranes. Meaningful outcomes: Digitization of membranes fabrication, reduce environmental impact of manufacturing processes.

M2DESCO (M2DESCO, Horizon-CL4-2023-RESILIENCE-01; 01/01/2024-31/12/2027) project is directed at addressing challenges for developing next-generation high-entropy-alloy-based multi-component green (free of toxic substances) and sustainable (rare earth free & minimum critical metal elements) coatings with predictable functionalities, performance and life - aiming at increasing wear resistance by 100%, corrosion/oxidation resistance by 50~60 %, and effectively reducing the criticality of coating materials by at least 70%. Objectives: the aim of the proposed project is to meet technical, ecological, sustainability-related challenges mentioned above collectively, for the development of much wider ranges of next generation green and sustainable multi-component high entropy coatings with designed functionalities, predictable performance, desired life-duration, dramatically reduced design and development cycle-time, through fully exploring such coating materials' and coating structures' potential, to be enabled by advanced multi-scale modelling. Meaningful outcomes: digital twins of materials and processes, economic benefits for manufacturing SMEs, improve skills and competencies in digital technologies.

RETECH (RETECH, H2020-ERAMIN2; 01/08/2020-31/12/2024). Through this project mineralogical, chemical and metallurgical studies related to integrating a full-scale enrichment research on industrial R&D projects will be conducted in Turkey. This project brings the opportunity to supply an alternative source of REE for Europe and Turkey. Obtaining strategically important REE from a deposit located in Turkey nearby to Europe can reduce dependency of our country and EU to overseas markets, especially to China largest supplier by introducing an alternative source and also it can ensure to have a sustainable and competitive supply chain and/or supply security. Based on policy of EU and Turkey created for ensuring diversity in energy source reducing dependency on foreign energy, results of this study will provide socio-economic impact and it will lead important achievements in technological progress. During the project, a realistic supply chain alternative to China will be simulated from ores to high technology magnet applications. Objectives: the overall objective of the project is to conduct R&D studies and develop efficient technologies for valorisation of rare earth elements (REEs) from existing complex ores, which will contribute to be established a sustainable REE supply chain in Turkey and Europe. This will be reached by the following specific objectives:

- Elaboration of the technology for mineral processing, leaching and obtaining RE concentrates;
- Elaboration of the solvent extraction process for efficient separation of rare earth oxides (REOs) from concentrates;
- Preliminary studies regarding obtaining of Nd-riched metals;
- Experimental studies regarding potential applications of REOs as dopants in sintered materials and thin films in addition to RE metal-based magnets.

Meaningful outcomes: New business model, new workplaces to be created.

5.5 Mineral Sector

5.5.1 State of the art of the Energy Efficiency in the minerals sector

The mineral sector uses a significant amount of energy, such as electricity, in all the processes of the mineral industry. For this reason, this sector aims at reducing its energy consumption and promoting EE initiatives for reducing its energy costs (Curry, Mansel, & Graeme, 2014) and climate-change impacts as well as the products' carbon footprints. In this context, growing energy demand has led to increase the use of renewable energy sources (McLellan, Corder, Giurco, & Ishihara, 2012), such as solar energy in mines' energy supply (Paredes Sánchez, 2018). An energy recovery system on diesel electric drive mine hauling trucks using simulations (Terblanche, Kearney, Hearn, & Knights, 2018) has been studied. In addition, electrical energy consumptions in mining operations treating sulphide ores has been investigated (Morán, Sbarbaro, Ortega, & Espinoza, 2019). As sulphide ores represent 80% of the total primary copper production, the energy demand and the characterization of electrical energy consumption of the different processes to mine and process sulphides ores were analysed described. In addition, a framework to assess dragline EE through the use equipment monitoring data (Abdi-Oskouei & Awuah-Offei, 2018) has included a three-step approach involving: (1) evaluating EE using data from dragline monitoring systems to estimate an overall performance indicator; (2) quantifying relationships among different operating parameters and the EE indicator; and (3) improving EE performance of operators, through the results in order to optimize operator training. Finally, plant process control and real-time optimisation approaches have been considered and described (Bouchard, Sbarbaro, & Desbiens, 2018). They were used to reduce energy requirements through lowering variability in key process variables and determining more appropriate operating points. In general, holistic, systems-based approaches will aim at optimizing EE and facilitating the integration of renewable energy sources into mines.

Over the last few years, several research and development initiatives have been launched focusing on circular CO_2 innovative solutions. In particular, some projects aim to reduce CO_2 process related emissions through carbon capture and use, improve energy efficiency, lower environmental impact as well as to reduce the carbon footprint in the production.

5.5.2 Projects on Energy Efficiency in the Mineral sector

INTMET (INTMET, H2020; 1/02/2016-31/01/2019) "Integrated innovative metallurgical system to benefit efficiently polymetallic, complex and low grade ores and concentrates". The INTMET approach represents a unique technological breakthrough to overcome the limitations related to difficult low grade and complex ores to achieve high efficient recovery of valuable metals (Cu, Zn, Pb, Ag) and CRM (Co, In, Sb). Main objective of INTMET is applying on-site mine-to-metal hydroprocessing of the produced concentrates enhancing substantially raw materials efficiency thanks to increase Cu+Zn+Pb recovery over 60% vs. existing selective flotation. 3 innovative hydrometallurgical processes (atmospheric, pressure and bioleaching), and novel more effective metals extraction techniques (e.g. Cu/Zn-SX-EW, chloride media, MSA, etc.) will be developed and tested at relevant environment aiming to maximise metal recovery yield and minimising energy consumption and environmental footprint. Additionally secondary materials like tailings and metallurgical wastes will be tested as well for metals recovery and sulphur valorisation. The technical, environmental and economic feasibility of the entire approaches will be evaluated to ensure a real business solution of the integrated INTMET process. Objectives: to apply on-site mine-to-metal hydroprocessing of the produced concentrates. Meaningful outcomes: comminution and flotation improvements and production of samples from the developed processes. Newly developed flotation reagents and microwave techniques have been applied. Development of Integrative Atmospheric Leaching Process: Obtained results at lab and pilot scale have shown the high recoveries as expected (e.g. 94% Cu and 95% Zn recovery). It can be stated that a new technological approach has been developed to treat efficiently reserves of polymetallic primary sulphides by means of hydroprocessing. Development of Integrative Pressure Leaching Process: Lab as well as pilot results obtained showed high Cu and Zn yields (Cu 95%, Zn 99%). Development of integrative bioleaching process: The results indicated maximum extractions achieved of 85% Cu, 75% Zn, 90% Pb, 90% Au and 80% Ag.

ITERAMS (ITERAMS, H2020; 01/06/2017-30/11/2020) "Integrated mineral technologies for more sustainable raw material supply data science, recycling" reinvented water and waste in mining. The new methods developed in the project offer the EU the potential to be in the forefront with regard to minimal waste, minimal energy and minimal water consumption in the mining sector. The ITERAMS project targeted significantly reducing water consumption by circulating process waters and reducing the amount of tailings waste through valorisation of the mineral matrix. Water circulation reduces water consumption at mine sites and the need to dispose of large quantities of wastewater in surrounding areas. Objectives: reducing water consumption by circulating process waters and reducing the amount of tailings waste through valorisation of the mineral matrix. Meaningful outcomes: new sensors for measuring ion concentration in water streams have developed, based on Ion-Selective Electrodes (ISE). Conceptually, a water treatment protocol has been developed, to guide interested users towards a promising and effective water treatment design, for a mine site. ITERAMS achieved a better understanding of conditions that are suitable for creating geopolymers from tailings obtained from ore processing and was able to successfully create these geopolymers and validate the models and concepts in relevant tests. A sustainability assessment for mine sites has been developed and successfully applied, that is at the same time able to capture the various sustainability effects of a mine operation, on-site and to local communities, as well as through the supply chain and life cycle, for environmental, social, and economic impacts.

COLUMBUS (COLUMBUS, Strategic Forum for Important Projects of Common European Interest (IPCEI)–via EU Innovation Fund; 2022–2025) project is based on carbon capture and methanation technologies. Objectives: Columbus project aims to reduce carbon emissions by transforming CO_2 generated during the lime production process into e-methane, which can be injected into the gas network or used to power vehicles and industry. Meaningful outcomes: the process up-scales and combines existing and emerging technologies, such as the fabrication of hydrogen, using some of the world's largest electrolysers and a new type of lime kiln to generate purer CO_2. The green hydrogen will be produced by a 75 MW electrolyser plant powered by green electricity. The Columbus project will open new routes for significant carbon emission reductions in Europe and the world.

NKL (NKL, National (BE) GreenWin; 02/2022–01/2026) Neutral Kero Lime (NK) is a study of an innovative e-Kerosene process using CO_2 from a lime kiln and hydrogen produced from green electricity. The capture of CO_2 at the lime plant would leverage some energy recovery from the synthetic kerosene via the Fischer-Tropsch process that converts a mixture of carbon monoxide and hydrogen or water gas into liquid hydrocarbons.

5.6 Water Sector

5.6.1 State of the art of the Energy Efficiency in the water sector

The European manufacturing industry consumes about 37,000 million m3/y freshwater recycling it up to 10 times with the specific electrical energy consumption >0.2 kWh/m3. By the according energy consumption of 74,000 GWh/year an potential 10 % savings will sum up to 7,400 GWh/year.

Currently, there is neither a benchmark on the energy consumption in industrial water circuits, nor tools for its systematic reduction, nor awareness of the saving potential.

The sustainable use of water is one of the top priorities for the industries being used for process and heat transfer purposes. A guide to help companies and industrial parks to reduce their water footprint and increase their overall sustainability into the future has been prepared by the ECO Efficiency Center (Centre). Industries become increasingly aware that they contribute directly and indirectly to water scarcity and pollution, and that this constitutes a risk they have to respond to. Therefore, a growing number of companies have started to explore their water footprint (WF) and to search for ways they can become better water stewards. The paper (Arjen, 2015) discusses what new perspective the WF concept brings to the table compared with the traditional way of looking at water use.

Different industries consume different quantities of water, depending on the characteristics of the industry, the technologies used in production processes, and so forth. All industries should develop and use cleaner production processes as well as reducing their water consumption and the wastewater discharged by the production processes (Qian, 2016).

Converting wastewater into energy or other resources is a new concept and a new direction for wastewater treatment, which has been discussed for the past three decades. Engineers have made great efforts in developing and applying new processes and technologies for wastewater reuse. Today, the use of wastewater as a water resource and as an energy resource has become a major strategy in the sustainable management of water resources.

After manpower, energy is the highest operating cost item for most water and wastewater companies. Over the last decade, energy consumption by the sector has increased considerably as a consequence of the implementation of new technologies to meet new potable water and effluent treatment quality standards. The price of energy has also increased substantially in the same period. These increases will be compounded by the need to meet future changes to regulations and standards that will require additional energy intensive processes to achieve more exacting requirements. High energy consumption will affect the water industry world wide and is inextricably linked to the issue of Climate Change (Brandt, Middleton, Wheale, & Schulting, 2011).

The best opportunities for energy cost savings in the water and wastewater industry involve electricity efficiency improvements. In particular, advancements to the large energy end-uses of pumping, aeration, and sludge treatment, offer the best savings potential. Because pumping accounts for over 80% of total electricity use in public water supply systems and for over 50% in wastewater treatment facilities, improvements in pumping efficiencies can generate substantial energy savings for the water and wastewater industry. Electric efficiency measures with the greatest energy cost savings potential include: regular infield pump testing to determine actual pump performance and the need for repair and replacement; the use of variable frequency drives (VFDs) to control pump speed and flow rather than throttling valves for fixed-speed drives; the use of Supervisory Control And Data Acquisition (SCADA) systems to optimize pumping performance continually; and replacing older, inefficient motors with high-efficiency or premium-efficiency motors (Carns, 2005).

Usually the water circuit simulation involves a series of fluido-dynamic parameters: part of them are measurable but there are also effects which are not directly measurable (such as, for example, the characteristics of the fluid or working regime and so on). These effects have a strong influence on the water circuit behaviour and are necessary for the simulation (without them the accuracy of the results is compromised) but they cannot be directly introduced in a fluid-dynamics tool. The use of techniques, that start from historic and measured data, can provide information capable to efficiently tune the global approach.

Combined cooling, heating and power (CCHP) system is drawing great attention due to its energy-saving, environmentally friendly and cost-saving characteristics. Conventionally, CCHP system uses the water–LiBr absorption chiller to meet the cooling demand. (Zhang Jiaxuan, 2018).

5.6.2 Projects on energy efficiency in the Water sector

The **WaterWatt** H2020 project aims to remove market barriers for energy efficient solutions, in particular the lack of expertise and information on energy management and saving potential in industrial water circuits.

In this project the improvement of energy efficiency in industrial water circuits for cooling, heating or transport will be addressed. These are auxiliary electric motor driven systems with a high optimisation potential (http://www.e3-waterwatt.net/).

WasteWater Treatment Plants (**WWTPs**) is one of the most expensive public industries in terms of energy requirements accounting for more than 1% of consumption of electricity in Europe. EU Water Framework Directive (WFD) 91/271/CEE made obligatory wastewater treatment for cities and towns. Now within the EU-27, the total number of WWTPs is estimated as 22.558, for which we can estimate a total energy consumption of 15,021 GWh/year. Although most of the objectives of the WFD in relation to water protection have been achieved, most of these aging plants show unsustainable energy consumption and must be optimized to the maximum and renovated accordingly. However, in Europe there is no legislation, norms or standards to be followed, and as consequence, a gigantic opportunity for reducing the public electric expense remains unregulated. ENERWATER (H2020, Mar 2015 - Feb 2018, http://www.enerwater.eu/) develops, validates and disseminates an innovative standard methodology for continuously assessing, labelling and improving the overall energy performance of Wastewater Treatment Plants (WWTPs). ENERWATER devoted important efforts to ensure that the methods are widely adopted. Subsequent objectives are to impulse dialogue towards the creation of a specific European legislation following the example of recently approved EU directives, to establish a way forward to achieve EU energy reductions objectives for 2020, ensuring effluent water quality, environmental protection and compliance with the FWD.

The **ECWRTI** (H2020, Jun 2015 - May 2019, https://cordis.europa.eu/article/id/241015-designing-a-full-recycling-solution-for-the-textile-industrys-waste-water and https://ecwrti.eu/objectives/) "Reuse of wastewater from the textile industry" project sets a leading industrial example by demonstrating the scale-up of the EColoRO concept. The EColoRO concept is ground breaking because it offers both a technically and an economically viable solution against low investment costs that closes the water cycle in the industry, achieving an unprecedented sustainability performance. The EColoRO concept uses electro-coagulation combined with flotation to remove pollutants, colorants and chemicals from wastewater very effectively. This unique feature enables using ultrafiltration and reverse osmosis membrane processes downstream in an optimized way. The goal of maximum resource and energy efficiency water and wastewater treatment is achieved with minimal use of chemicals and consumables in water treatment, minimizing use of energy and preferably using available waste heat sources.

iWAYS (iWAYS, H2020; 01/12/2020 – 30/11/2024) "Innovative water recovery solutions through recycling of heat, materials and water across multiple sectors". Industrial white plumes are an unexploited source of water and energy as these gaseous emissions represent one of the main streams that discharges used water during the manufacturing of ceramics, chemical products, steel, food, paper pulp, aluminium and other industrial goods. Thus, transforming these industries towards near zero discharge water to reduce exhaust gases, recover water and energy, transforming industry constitutes an exciting and strategically important action to meet the policy goals of the European Green Deal. State-of-the-art technologies have though not succeeded in meeting the challenges associated such as cost-effectiveness and robust integration with the manufacturing process, and hence these white plumes continue being an important loss of water and energy.

This is the principal challenge the iWAYS project will solve by developing a set of technologies capable of recovering water and energy from exhaust gases for productive use in the industrial process. Objectives: Realizing water closed loops and a substantial reduction in freshwater consumption while achieving a substantial reduction in thermal waste and process energy requirements. Reclaiming, treating and reutilizing water in industrial processes. Results: Significant reduction of the current use of fresh water resources: at least 30% reduction of freshwater consumption in the considered use cases and significant increase of the recovery of water, energy and/or substances: 30% water and heat recovery from humid exhaust gases along with recuperation of materials included in the flue stream. Contribution to regulation and standards. Development of learning resources with flexible usability will be integrated in existing curricula and modules for undergraduate level and lifelong learning programmes.

SPOTVIEW (SPOTVIEW, H2020; 03/10/2016-02/04/2020) "Sustainable Processes and Optimized Technologies for Industrially Efficient Water Usage". The volume of freshwater used by process industries represents 25 billion m3 per year in Europe and accounts for 10% of total water consumption. Steel, Paper and Dairy sectors contribute to 36% of industrial water uptake, and 18% of eqCO_2 emissions. The objective of the SPOTVIEW project is to develop and demonstrate innovative, sustainable and efficient processes and technology components, in order to optimize the use of natural resources, especially water, in three industrial sectors (Dairy, Pulp and Paper and Steel) contributing to 44% of industrial water usage in EU. This resource optimization (including water, energy, raw materials and additives) is a key issue to maintain production competitiveness and sustainability. Objectives: Recover and recycle valuable substances and energy (heat, biogas) from process water; Reuse treated water to reduce discharges; Substitute freshwater with alternative water sources. Meaningful outcomes: the technologies studied showed high potential for reducing fresh water intake (23% for dairy, 22% and 58% for pulp & paper and up to 68% for steel). Reduction of at least 30% in waste water production has been demonstrated for all sectors: dairy 29%, pulp & paper 29%/58% and steel up to 75%. The energy reduction target was achieved by waste water reuse in pulp & paper (OCC and tissue). In dairy the target was almost achieved with 13% energy saving through biogas production. For steel the possible energy savings were limited to 2%.

5.7 Cement Sector

5.7.1 State of the art of the Energy Efficiency in the cement sector

Cement industry is one of the most energy intensive industrial sector and it accounts for almost 15% of the total energy consumed by manufacturing. Survey results on energy efficiency measures for raw materials preparation, clinker production, products and feedstock changes, general energy efficiency measures, and finish grinding have shown that on average, to produce one ton of cement, 3.4 GJ of thermal energy (in dry process) and 110 kWh of electrical energy are needed (Madlool, 2013). Furthermore, it has been described and forecasted a plausible course of development in the use of energy in cement production in Germany, in light of the agreement between the Federal Government and industry to reduce the level of energy consumption (Hoenig, et al., 2013). Results showed that the fuel energy demand rose with increasing substitution rate of fossil fuels by alternative fuels compared to the BAT 2011 scenario. This increase is primarily caused by the process-integrated drying of the alternative fuels. Additional heat losses are also caused by the increased bypass operation. The study of cement grinding has shown that the electrical energy demand increases in the long term assuming normal technical development of the grinding technology. However, it must be taken into account that the electrical energy demand for cement grinding represents only about half the total power requirement for cement production.

The cement sector is highly energy and material intensive causing more than 5% of the global CO_2 emissions and substantial emissions of SO_2, NO_x and other pollutants (IPPC, 2010). However, initiatives and studies in this sector have been focused on the improvement of energy efficiency. In particular, the recent application of energy efficiency in the Italian cement industry and the future perspectives of technologies has been described (Cantini, et al., 2021). A sample of plant was investigated through the analysis of mandatory energy audit considering the type of interventions they have recently implemented, or they intend to implement by identifying the degree of application and the future perspectives of the available technologies for improving energy efficiency in the Italian industry, also allowing to identify the main reasons for these choices and trends. the outcome is a descriptive analysis, useful for companies willing to improve their sustainability. Results have proved that solutions to reduce the energy consumption of auxiliary systems such as compressors, engines, and pumps are currently the most attractive opportunities. In addition, a recent study aims to reduce energy consumption and CO_2 emissions but at the same time maintaining the quality and capacity of production (Mokhtar, 2020). Four groups of technologies can be highlighted: energy efficient technologies, product and feedstock modification (i.e. manufacturing low alkali and limestone cements are alternatives to reduce the required thermal energy (Detwiler, 2003)), alternative fuels and recovering energy measures, CO_2 emission reduction systems (Atmaca, 2014). According to (Mokhtar, 2020) a decision making model has been developed in order to assist selection of energy efficiency measures.

The European cement industry roadmap to 2050 gives a general overview of the industry before looking at specific aspects. Clinker, cement, concrete, construction and carbonation are all reported on with regards to topics including alterntive raw materials, energy efficiency and alternative energy supplies, policy and training. This report also includes an assessment of different decarbonisation levers and risk assessment of roadblocks and opportunities (Cembureau, 2024). In particular, it includes the roadmap of pathways and levers to scale up the cement industry net zero ambition – pathway to 2050: -37% of CO_2 emissions on cement by 2023; -78% of CO_2 emissions on cement by 2040; -100% of CO_2 emissions on cement by 2050 (compared to 1990 levels).

Compared to the 2020 cement industry roadmap, the changes are:

- Based on progress to date (53% in 2021), alternative fuel objectives for 2050 have increased our from 90% to 95%.
- The clinker substitution ambition for 2050 to achieve a clinker to cement ratio of 60% has been revised, compared to 65% in the initial roadmap.
- Sufficient availability of clinker substitution materials will be a key driver in reaching this objective.
- A more detailed breakdown of CCUS volumes has been developed. Given the planned investments, we now have included a 2030 estimate for CCUS deployment.
- 2040 objectives for all levers have been included to be able to track progress and assess how can be aligned with the EU's objectives.

Substantial investments have allowed to set more ambitious reduction objectives for 2030. In 2020, a CO_2 emissions reduction of 30% on cement and 40% down the value chain were planned. This overall number to 37% on cement and 50% down the value chain was now revised.

Strong 2040 ambition for the cement sector: by combining all levers, a 78% reduction of CO2 emissions on cement by 2040, and of 93% down the value chain are estimated.

Potential for negative emissions over the value chain by 2050: with the ambition to reach net zero emissions on cement by 2050, the sector has the potential to become carbon negative over the value chain.

5.7.2 Projects on Energy Efficiency deeply involving the cement sector.

The projects related to the Energy Efficiency in the cement sector are:

1. **TASIO** ((TASIO, H2020 G.A 637189; 2014-2019) project has the main objective to develop a Waste Heat Recovery System (WHRS) based on the Organic Rankine Cycle (ORC) technology incorporating a new Direct Heat Exchange solution suitable for various Energy Intensive Industries: steelmaking, cement, glassmaking and petrochemical. This technology is able to recover and transform the thermal energy of the flue gases of Energy Intensive Industries into electric power for internal or external use. The WHRS has been developed and tested to recover and transform the thermal energy of the flue gases into mechanical energy. The project covers several relevant sectors of

the energy intensive industry, namely cement, steel, glass and petrochemical sectors. The industrial involvement in the project was significant and the installation at industrial scale of the WHRS for electrical energy generation in one of the partners has been carried out.

2. **ECO-binder** (ECO-binder, H2020; 01/01/2015-31/12/2018) "Development of insulating concrete systems based on novel low CO_2 binders" project aims to implement industrial R&D activities on the results of previous research, demonstrating the possibility of replacing Ordinary Portland Cement (OPC) and OPC based concrete products with new ones based on the new Belite-Ye'elimite-Ferrite (BYF) class of low-CO_2 binders to develop a new generation of concrete-based construction materials and prefabricated building envelope components with more than 30% lower embodied energy, 20% improved insulation properties and 15% lower cost than the actual solutions based on Portland cement. Objectives: reduction of buildings operational energy while complying with the load bearing features of existing building structures. Meaningful outcomes: Demonstration of full-scale retrofitting and construction will be performed prototyping and installing a family of prefabricated concrete systems of different complexity and end-use in four different climatic conditions involving public authorities.. Results will be validated through dedicated LCAs, fostering the construction materials sector progress towards increased performing and eco-sustainable products.
3. **BOOSTEE** (BOOSTEE, 2017-2020) project will develop and implement technical solutions, strategies, management approaches & financing schemes to achieve higher Energy Efficiency (EE) in public buildings. A transnational cooperation and by using geospatial data, smart energy management tools and energy audits to facilitate the implementation of EE buildings will be used. Objectives: The final aim is to improve the governance of Energy Efficiency in existing public buildings (within Pilot Actions) and ultimately reduce energy consumption.
4. **BHENEFIT** (BHENEFIT, 2017-2020) will improve the management of historic built areas, combining the daily maintenance of historic heritage with its preservation and valorisation in a sustainable way. Action plans and ICT implementations were developed to increase the cooperation among involved stakeholders in sustainable management of Historic Built Areas, enhance their awareness and skills, increase availability of data and information, monitor and plan through effective tools. Objectives: The project will look for novel solutions on how to evaluate the use and the historical value of built areas and how to optimise the building performances (its energy efficiency and structural behavioural increase). Meaningful outcomes: A comprehensive monitoring strategy has been developed which aims at the planned preservation of cultural heritage. To implement such strategy, BhENEFIT built management capacities, involved and coordinated relevant players from the public and private sectors and provided them with new innovative methodologies GIS and BIM based.
5. **RECODE** (RECODE, H2020; 1/08/2017-31/07/2022) "Recycling carbon dioxide in the cement industry to produce added-value additives: a step towards a CO_2 circular economy". CO_2 from the flue gases of a rotary kiln in a cement industry (CO_2: 25 vol%) will be used for the production of value-added chemicals (acid additives for cement formulations) and materials ($CaCO_3$ nanoparticles to be used as concrete fillers). A circular-economy-approach is enabled: the CO_2 produced by cement manufacturing is re-used in a significant part within the plant itself to produce better cement-related products entailing less energy intensity and related CO_2 emissions by a quadratic effect. Objectives: to promote the precipitation of nano-CaCO3 powders which act as strength enhancer and accelerator of the hydration rate; to synthesize through electrocatalytic and

catalytic pathways formic acid, oxalic acid and glycine to be used as hardening acceleration promoters, grinding aids or ionic liquids additives, respectively. Meaningful outcomes: there has been substantial progress regarding characterization and selection of IL-based absorbent systems that both cope with the harsh oxidative conditions found in the cement plant flue gas and enable effective chemical absorption of CO_2. The basic design of the CO_2 separation plant as well as for the gas pre-treatment and after-treatment was developed.

6. **C02OLHEAT** (C02OLHEAT, H2020; 01/06/2021–31/05/2025) "Supercritical CO_2 power cycles demonstration in Operational environment Locally valorising industrial Waste Heat" project intends to valorise waste heat even at a significant temperature of 400 °C if compared with the traditional steam/ORC solutions. The project will demonstrate the operation of a 2 MW waste-heat-to-power skid based on a 2MW-sCO2 cycle in the CEMEX cement manufacturing plant in the Czech Republic. Objectives: the objective is to demonstrate the EU MW scale first-of-a-kind waste heat-sCO2 plant towards a cheaper/more flexible waste heat valorisation.

5.8 Ceramics Sector

5.8.1 State of the art of the Energy Efficiency in the Ceramic Sector

One of the industrial sectors with the highest energy consumption is the ceramic industry. This sector consumes large amounts of energy during all its processes, but mainly during firing, which is responsible for 50-60% of the total energy consumed. During firing, furnaces can reach very high temperatures that range between 800 and 1200°C, which requires a significant consumption of fossil fuels, mainly natural gas (EIPPCB, 2007).

The thermal energy consumption mainly occurs during three process stages: spray drying of ceramic slurries (36%), drying of the formed ceramic tile bodies (9%), and ceramic tile firing (55%) (EIPPCB, 2007). The potential improvement of energy efficiency is particularly huge. Electricity consumption represents up to 30% of the production cost in ceramics processing, although it varies, based on product type and cost of fuel (Technology, 2012). A reduction in energy use and cost can therefore lower the production cost, whilst generating an immediate impact on profit (Ibn-Mohammed, 2019).

According to (BEIS, 2017), radical or incremental innovations related to both process innovations (e.g. electric field assisted sintering techniques or vacuum drying) and product innovations (e.g. zero-energy coatings) could be used in order to further reduce the energy needed in the processes.

5.8.2 Projects on Energy Efficiency deeply involving the ceramics sector.

H2020 and LIFE Projects related to Energy efficiency in the ceramics sector in the last ten years are:

1. **DREAM** (DREAM, 2016-2019) project aims to design, develop and demonstrate a radically improved architecture for ceramic Industrial furnaces, characterized by optimized energy consumption, reduced emissions, and lower operating costs compared to currently available technological solutions. This will be obtained by substantially enhancing specific furnace parts (control system, refractories, emissions abatement system) and

by adding new modules and subsystems (CHP unit, heat pipes) to the current furnace architecture. Objectives are:

- To design innovative hardware furnace components improving energy efficiency;
- To introduce substantial improvements on current hardware-software kiln parts;
- To demonstrate the DREAM solutions in a variety of industrial settings;
- To pave the way for a full seizure of DREAM related market opportunities.

Meaningful Outcomes: DREAM developed and demonstrated technologies enabling a significant advancement in the sustainability of ceramics processes, implementing 5 synergic lines of research and 3 industrial demonstrators, which will act as technological showcases for market deployment. Such approach will enable to advance, in the five lines of research, from TRL4 to TRL6. It will strongly contribute to both the sustainability and competitiveness of the European ceramics and process industries. In particular, the DREAM technologies will earn an overall 20% OPEX and energy consumption reduction for industrial furnaces, with an average investment payback time for end users lower than 3 years.

2. **LIFECERAM** project (LIFECERAM, 2013-2016) Objectives: the main objective was to achieve zero-waste in the manufacture of ceramic tiles. For this, two main objectives have been pursued: the development of a new type of ceramic tile for outdoor application (urban paving) that can incorporate in the body and glaze high content of ceramic waste and the design of a highly sustainable body preparation process for manufacturing the above ceramic tiles, based on dry milling technologies, capable of recycling all type of ceramic wastes. Other energy-intensive process wastes (from power plants or glass manufacturing) have been also considered. Other objectives:
   - Developing the new product from an environmental life cycle perspective.
   - Quantifying and characterizing all the wastes generated in the manufacture of ceramic tiles and related companies (body composition suppliers, glaze producers and polishing facilities) and those from energy-intensive processes next (100 Km distance) to the ceramic companies.
   - Designing body and glaze compositions able to recycle all types of ceramic waste.
   - Scaling-up the laboratory results to the industry and determining the new process variables
3. **ENVIP** (ENVIP, 2013-2015) project. Objectives: constructing on a pre-industrial scale a prototype facility or forming sanitary wares by isostatic pressing of granulated body. This innovative technology is a promising alternative to the traditional method. Other objectives are:
   - Eliminate the water consumption associated with the traditional forming process by pressure slip casting;
   - Reduce the volume of wastewater generated in the process;
   - Reduce energy consumption and CO_2 emissions;
   - Identify the optimal conditions for the industrial forming process of sanitaryware with different geometries and dimensions;
   - Validate the compositions for different ceramic pastes used in the isostatic pressing process;
   - Disseminate the environmental improvements achieved with the new forming technology across the EU;

  - Identify, validate and communicate the application of this innovative technology, which can be potentially considered as a Best Available Technique to update the BREF in the sanitary wares' industry.

Meaningful Outcomes: the construction on a pre-industrial scale of a prototype facility, for forming sanitary wares by an innovative technology based on isostatic pressing of granulated body was developed and validated at the beneficiary's factory in Gavà, Barcelona. This technology had never been used before in sanitary manufacturing.

4. **LASERFIRING** project (LASERFIRING, 2010-2013) Objectives: it aimed to develop a new method for manufacturing structural ceramics using laser technology in the firing phase, allowing firing at lower temperatures. In the particular case of refractory bricks, the new process would reduce the firing temperature from 1 300 ºC to 900 ºC, without compromising the aesthetic or structural properties. The laser technology would replace part of the firing step. Laser surface treatment allows the conservation of the technological properties of the ceramics, even at a lower firing temperature. The new procedure requires a new drying system and a new furnace in which the laser tool will be integrated. This new approach would allow the firing temperature to be reduced by between 100 and 500 ºC, resulting in a considerable reduction in GHG emissions in the structural ceramics industry. Meaningful Outcomes: The LASERFIRING project achieved all its targets: the beneficiaries set up and validated a prototype for the development of a new line of ceramic products for the building industry, which reduces CO_2 emissions. The prototype achieved reduction of 40%, in the best cases, and of 10% in the worse ones. It also showed that for products that have higher treatment temperatures in the conventional process the possibilities for reduction of CO_2 emissions by means of the 'LASERFIRING' process are greater. The LASERFIRING technology and process is up scalable to a semi-industrial process for some materials and sectors such as wall and ceramic tiles. The beneficiary believe that it could be feasible to install 10 LASERFIRING furnaces of medium size (300 tonnes/day) in the next 10 years. This entails a production of 1 100 000 tonnes/year that will lead to a reduction in CO_2 emissions of 90 000 to 15 000 tonnes/year, depending on the decrease of the treatment temperature. The reduction of emissions and the energy savings may be quantified, depending on the starting mineral composition. Energy savings and reduction of CO_2 emissions have been achieved for:
   - White firing clay – 28-34%;
   - Red fired clays – 10-14%;
   - Black bricks – about 35%;
   - Gressified clay – 20-30%.
5. **DOC3D** project (DOC3D, 2018-tbc) will train a new generation of Early-Stage Researchers (ESR) to develop the whole value chain of ceramics 3D printing from elaborating feedstock to testing in products for commercialization. High-value ceramics are widely utilized in high-end engineering disciplines due to their low density, Outstanding mechanical strength alongside with their excellent thermal, corrosion and wear resistance for aerospace, and medical applications. However, conventional manufacturing techniques are time-consuming and show several limitations, such as geometrical variation induced by the shrinkage during sintering and low material yield, alongside with high tool wear during milling and machining. As of today, these drawbacks impede the industrial utilization of these ceramic materials for a growing range of engineering

and medical disciplines. DOC 3D Printing will cover the whole value chain of ceramics 3D printing, from laboratory research to product development. Objectives:

- to develop feedstock customised for 3D-printing (AM) at reduced cost;
- to design and build next generation of 3D printers and strategies specifically dedicated to ceramics production (net-shape ceramics faster with desired properties & design at reduced cost);
- to correlate input to output produced ceramics and demonstrate it for applications;
- to define and establish standardisation, regulatory issues, qualifications and risks analysis;
- to increase knowledge on modelling & characterizations and develop specific tools for that.

Meaningful Outcomes: The close interactions between academic and non-academic sectors within research activities is a key aspect of the project in order to transfer scientific knowledge to the market and close the gap of the death valley, and to strengthen the education of PhD fellows through the relevant skills and an enhanced competitiveness.

6. **HEART** project (HEART, 2013-2017) Objectives: demonstration of the feasibility of a thermal recovery system for the clay and roof tile industry that combines a low temperature and corrosion resistant heat exchanger (on the kiln fumes) and an industrial ammonia heat pump (on the dryer fumes). The pilot system have been installed in a roof tile factory in south-west France. The recovered heat has pre-heat the air inflow into the dryer. The water condensed by the heat pump have been reused to moisturize clay for the shaping of the products in place of the use of more water. The heat exchanger on the kiln fumes would clean these fumes from their volatile pollutants (fluorine, sulphur, chlorine) by producing acid concentrates that would be neutralized. The project aimed to show that a significant part of the thermal losses of a clay brick or roof tile production unit could be recovered and reused in the process; and that the new recovery system could be retrofitted easily and safely into an existing clay brick or roof tile factory. Other specific goals included: Recovery of water by condensing steam for re-use in the clay process, thereby significantly reducing water consumption; purification of the kiln fumes of volatile pollutants; and a new standard for clay brick and roof tile technology. Meaningful Outcome: For the demonstration production unit, the target was to reduce by around 25% the consumption of natural gas and the associated CO_2 emissions, and by 90% the consumption of water, compared to 2011 figures under normal activities.
7. **NanoCeramiCO2** (NanoCeramiCO2, 2014-2017) project's Objective: reduction of the natural gas consumption and carbon dioxide (CO_2) emissions from the firing of ceramic materials in a factory producing bricks and roof tiles. This goal would be achieved through an innovative method that uses calcium carbonate ($CaCO_3$) nanoparticles in raw materials, which enables the firing temperature to be reduced. The project would design and develop a prototype to produce calcium carbonate ($CaCO_3$) nanoparticles and introduce them into the ceramic mass in order to obtain a homogeneous mixture. The project would test the firing of the mixture at semi-industrial and industrial scale. In particular, the project would:
   - Analyse the chemical and mineralogical composition of the clays that will be used as raw material;
   - Determine the optimum composition of the calcium carbonate mixture, in order to achieve the greatest energy saving and the maximum emissions reduction;

- Establish a process for adding nanoparticles to the raw material to produce a homogeneous mixture;
- Demonstrate the process at industrial scale;
- Analyse the resulting ceramic material, and demonstrate its viability in structural applications; and
- Conduct an environmental analysis of the industrial process.

Meaningful Outcomes: it was estimated that a 14°C reduction in the firing temperature for bricks and tiles would result in an 8% reduction in energy consumption, and a reduction of 17.1 kg/CO_2 per tonne of fired product. Because of the small quantity of $CaCO_3$ nanoparticles used, the CO_2 emissions produced by its decomposition are very low and are not relevant in comparison with the CO_2 emissions generated during the firing process. Previous tests have achieved a temperature reduction greater than 14ºC, and the project estimates that an overall energy saving of 10% can be achieved in the firing process, leading to a CO_2 emissions reduction of 1800-4500 tonnes/year.

8. **LIFE CERSUDS** (LIFE-CERSUDS, 2016-2019) project Objectives: improvement of the resilience of cities to climate change and promotion of the use of green infrastructure in their urban planning as a means of managing surface water flooding. It aimed to achieve this goal through the development and implementation of a demonstration low-carbon Sustainable Urban Drainage Systems (SUDS). The system would consist of an innovative permeable surface with a very low environmental impact, based on the use of tiles with low commercial value. Specifically, the project aimed to:
    - Reduce flooding caused by torrential rain by increasing the number of permeable surfaces in cities;
    - Re-use water stored during the rainy season for use during periods of drought;
    - Reduce runoff volumes and peak flows to treatment plants and receiving water bodies;
    - Integrate treatment of rainwater into the urban landscape;
    - Protect water quality by reducing the effects of diffuse pollution and thus avoiding problems in sewage treatment plants;
    - Reduce CO_2 emissions linked with the manufacture of pavements for SUDS, given that the project will use ceramic materials with low commercial value, giving ceramic tile manufacturers a new revenue stream;
    - Provide an aesthetic SUDS and prevent ponding, increasing the comfort and safety of streets in rainy weather;
    - Develop a ceramic SUDS with greater environmental efficiency;
    - Demonstrate that this ceramic SUDS is suitable for rehabilitating urban areas with light traffic and to enable better management of rainwater in areas with particular geo-economic conditions;
    - Guarantee transferability beyond the end of the project through training activities and a business plan aimed at engineers, architects and companies, and by increasing local authorities awareness;
    - Generate precise technical documentation to facilitate replication in other cities based on the principles of the LIFE CERSUDS demonstrator.

Meaningful Outcomes: design and production successfully of a ceramic tiled pavement in the Spanish city of Benicssim, highlighting numerous environmental benefits throughout the application and use of this innovative low carbon permeable surface that manages surface water flooding. During the project, the system received more than 1 000 m^3 of rainfall, from which 86% was managed by the system, either through collection for future use (7.8%), infiltration in the ground or evaporation into the atmosphere (78.2%).

9. **CELL3DITOR** (CELL3DITOR) is a project dealing with the Solid Oxide Fuel Cell (SOFC) which is a ceramic based multilayer device that involves expensive and time-consuming multi-step manufacturing processes including tape casting, screen printing, firing, shaping and several high-temperature thermal treatments. Objectives: the Cell3Ditor project is designed to enable the quick deployment of 3D mass manufacturing technology of SOFC stacks. The main goal of the Cell3Ditor project is the development of a 3D printing technology for the industrial production of SOFC stacks by covering research and innovation in all the stages of the industrial value chain. Meaningful Outcomes: all-ceramic joint-free SOFC stacks with embedded fluidics and current collection will be fabricated in a two-step process (singlestep printing and sintering) to reduce in energy, materials and assembly costs while simplifying the design for manufacturing and time to market. Compared to traditional ceramic processing, the Cell3Ditor manufacturing process presents a significantly shorter time to market (from years to months) and a cost reduction estimated in 63% with an initial investment below one third of an equivalent conventional manufacturing plant (production of 1000 units per year).
10. **ECONOMICK** (ECONOMICK, 2016-2019) project sought to help the European ceramic sector to reduce environmental impacts and increase competitiveness, by developing an innovative intermittent kiln for ceramic production that consumes about 45% less energy than actually existing ones and, consequently, allows the industry to reduce costs, CO_2 & pollutant emissions, and raw materials consumption. Objectives: The innovative shuttle kiln that was developed will have applications in the firing of sanitary ware, tableware and refractories. As well as energy savings, ECONOMIK is expected to result in reduced CO_2 and NOx emissions and reduced raw material consumption. ECONOMIK kilns are also expected to reduce operating costs and improve production flexibility. Meaningful outcomes: a pilot energy efficient intermittent kiln, with the following performance:

    - 45 % lower energy consumption and combustion emissions (CO_2) than state-of-the-art intermittent kilns;
    - equal qualitative performance and flexibility than state-of-the-art intermittent kilns;
    - 4,220 sanitary-ware and 30,000 tableware pieces produced with the ECONOMICK kiln, with equal quality to those normally produced by the collaborating companies;
    - Effective environmental benefits thanks to reduced methane consumption and reduced emissions of NOx, HF and Dust;
    - Broad international awareness on the newly available kiln, by open day/seminar for sanitary ware manufactures, national and international conferences, awareness-raising initiatives at international fairs and several communication tools;
    - 4 networking workshops to strengthen collaboration opportunities;
    - An environmental Life Cycle Assessment (LCA), a Life-cycle-costing and a Social LCA report, with conclusions and recommendations;

- A set of business cases and a sound business plan for putting the innovation onto the market.

11. **ULTIMATE CERAMICS** (CERAMICS, FP7; 01/02/2012-31/10/2017) “Printed Electroceramics with Ultimate Compositions” Electroceramics have a multibillion market with applications in the field of high frequency telecommunication, electronics, and different kinds of sensors, actuators and energy harvesters. The devices made of electroceramics can be found everywhere like in mobile phones, cars, cameras, computers, telescopes, lightning, toys, medical and space devices etc. However, the fabrication temperature of electroceramic devices is commonly well over 1 000 °C, one small exception being the Low Temperature Co-fired Ceramics with sintering temperature of 850-900 °C. In this project we have been able to develop new electroceramic composites which fabrication temperature is in the range of 450 - 20 °C (room temperature). Objectives: develop new electroceramic composites which fabrication temperature is in the range of 450 - 20 °C (room temperature). Meaningful outcomes: these temperatures enable also devices with different materials (other ceramics, polymers, metals) integrated into a same device in one production step reliably, with very low energy consumption and low cost investments, utilizing also environmentally friendly materials. In addition these materials can be 2D and 3D printed needing no extra heating (e.g. by laser) arrangements. These ground breaking achievements open up new business opportunities to large and small scale industry.
12. **CoACH** (CoACH, H2020; 01/01/2015-31/12/2018) “Advanced glasses, Composites And Ceramics for High growth Industries” aims at offering a multidisciplinary training in the field of high-tech GLASSES, CERAMICS and COMPOSITES based on effective and proven industry-academia cooperation. Our scientific goals are to develop advanced knowledge on glass and ceramic based materials and to develop innovative, cost-competitive, and environmentally acceptable materials and processing technologies. Objectives: the research programme approach to new glass- and ceramic- based materials and their applications. Meaningful outcomes: Advanced materials fall within the KEY ENABLING TECHNOLOGIES (KETs) and are themselves an emerging supradisciplinary field; expertise on these new materials brings competitiveness in the strategic thematic areas of: HEALTH-innovative glass and composite for biomedical applications, ENERGY-innovative glass, ceramic and composite materials for energy harvesting/scavenging, solid oxide electrolysis cells and oil, gas and petrochemical industries, ICT-new glass fibre sensors embedded in smart coatings for harsh environment, ENVIRONMENT-new and low cost glass, ceramic and composite materials from waste.
13. **DRYficiency** (DRYficiency, H2020-EE-2016-PPP (SPIRE); 01/09/2016-31/08/2020) “Waste Heat Recovery in Industrial Drying Processes”. Objectives: The overall objective of the DRYficiency project is to lead energy-intensive sectors of the European manufacturing industry to high energy efficiency and a reduction of fossil carbon emissions by means of waste heat recovery to foster competitiveness, improve security of energy supply and guarantee sustainable production in Europe. The project addresses three sectors, namely brick, pet care/feed and food industry. The results are however of major relevance for a number of other energy-intensive industries such as e.g. pulp and paper industry. Meaningful outcomes: the key elements of the solution are three high temperature vapour compression heat pumps: two closed loop heat pump for air drying processes and one open loop heat pump for steam drying processes. The DryFiciency consortium elaborated technically and economically viable solutions for upgrading idle

waste heat streams to process heat streams at higher temperature levels up to 180 °C. The DryFiciency solution has been demonstrated under real production conditions in operational industrial drying processes in three leading European manufacturing companies from the pet food, food and brick industries.

14. **IbD** (IbD, H2020 - SPIRE 8 - 2015 Grant Agreement no. 680565; 2015-2018) "Intensified by Design® for the Intensification of Processes involving Solids Handling". The Intensified-by-Design (IbD) Project has created a holistic platform for facilitating process intensification design and optimization in processes in which solids are an intrinsic part. The project has developed and upgraded methods for the handling of solids in continuous production units based, on the one hand, in the intensification of currently existing processes and, on the other hand, through completely new approaches to the processing of solids. IbD is the new paradigm in the intensification of processes based on statistical, analytical and risk management methodologies in the design, development and manufacturing of high quality safe and tailored chemicals, pharmaceuticals, minerals, ceramics, etc. under intensified processes. Objectives: IbD will make a landmark advance in bridging the technological and knowledge gaps in the area of Process Intensification in processes involving solids. It will create a comprehensive devices- and processes design-platform for the industrial realization of Process Intensification involving solids handling. I will bring to the industry an ergonomic, flexible, scalable IbD platform that performs fast reiterations of processes and device designs. Meaningful outcomes: No comprehensive software is currently available for assisting the process engineers to design solutions based on Process Intensification. Therefore, the IbD Platform will be a disruptive tool for widely fostering PI beyond the scope of the IbD Project. The Platform will have a built-in TRIZ module to assist the practitioners to ideate innovative solutions which have not been created yet.
15. **LIFE SUPERHERO** (SUPERHERO, LIFE19 CCA/IT/001194, 2020-2025) "Energy-efficient roofs for sustainable low-cost climate adaptation". Ventilated and permeable roofs (VPRs) made from clay tiles can provide a sustainable climate adaptation and mitigation technology, which considerably reduces the energy required to cool buildings. Objectives: the LIFE SUPERHERO project team, coordinated by Centro Ceramico, will demonstrate the benefits of the technology by renovating two buildings in Reggio Emilia. They aim to increase the use of VPRs by producing a standardised roof air permeability test method, and updating regulations, standards and green rating systems to include VPRs. Meaningful outcomes: the team will also release a decision-support tool for building design, and upgrade a roof tile production line in Italy to produce the new VPR tiles.
16. **NEOSAWARE** (NEOSAWARE, H2020, 01/12/2019-31/05/2020) "Modelling software platform for ceramic body optimization". The ceramic industry faces new challenges in an innovative and highly competitive global market. Long trial-and-error improvement processes represent today the major obstacle to competitiveness. Enhancing ceramic body composition is instrumental to developing new products, increasing profitability and reducing environmental impact. Traditional methods are not efficient, while the learning process requires at least 2 years to achieve the desired result. The EU-funded NEOSAWARE project proposes a software solution based on artificial intelligence, computer simulation and mathematical optimisation to hasten the learning process. The solution will allow the industry to carry out highly precise forecasts during the manufacturing process and on the final product. The solution reduces production costs, guarantees quality standards and decreases environmental impact. Objectives: apply-

ing Artificial Intelligence, computer simulation and mathematical optimization to accelerate by an order of magnitude the learning process which leads to optimal ceramic body compositions. Meaningful outcomes: carried out a detailed assessment of Media Market working strategies, characterizing the target market and its main drivers and trends. We have analysed also the Intellectual Property (IP) and regulation aspects; We have defined in detail the technical needs and objectives for Next Phase; and we have analysed the main threats and opportunities for our enterprise in general and for NEOSAWARE as its core product, giving as a result a throughout financial estimations for our SME as a high-growth business and a clear fully-market oriented innovation roadmap for Next Phase and beyond.

17. **GreenBricks** (GreenBricks, AT: FFG/NEFI(New Energy For Industry);01/10/2022-03/09/2025) Currently, high-temperature tunnel kilns fired with natural gas are used for firing products in the industrial brick and heavy clay industry. The production processes result in high energy-related CO_2 emissions, and further CO_2 emissions come from the release of carbonates contained in the clay and the combustion of additives. Objectives: to decarbonise the industrial production of bricks, GreenBricks goals are:
    - holistic optimisation of the brick manufacturing process.
    - development of new CO_2-neutral clay mixtures considering site-specific product and clay properties as well as industrial production environments.
    - optimisation of the overall energy efficiency in the dryer - burner - heat pump heat network and adaptation of the brick drying technology to the new electric kiln and clay recipe.
    - optimisation of the operation of the novel, high-efficiency, high-temperature tunnel kiln.
    - scaling up the concept and evaluating its transferability to other production sites and technology transfer to related sectors.
    - securing social acceptance and trust in the developed solutions.

    In order to optimise the process of brick production holistically, various tools / technologies are being developed in GreenBricks. This includes, above all, the creation of a digital twin of the dryer-burner-heat pump heat network as well as a model for techno-economic optimisation at the plant level. Meaningful outcomes: GreenBricks should lead to the following results:
        - Enabling a holistic view of the entire production process through its further digitalisation.
        - New, robust, clay mixtures with no or minimal CO_2 content.
        - World's first large-scale demonstration of a CO_2-neutral kiln for brick firing, leading to a reduction of CO_2 emissions at the demo site by up to 88%.
        - Roll-out concepts for at least five additional Wienerberger sites as well as broad knowledge about the technical feasibility of electrifying various burner types for the production of different products in the ceramics industry and beyond.
        - Broad public awareness and acceptance of the research work carried out and results achieved.

Regional projects dedicated to the Energy Efficiency in the ceramics industry are:

1. **MAGF** (MAGF, 2014-2017) project: when firing ceramics with conventional methods, the surface of the product heats readily whereas the interior relies on slow heat conduction. This results in low heating rate and long production time to obtain an evenly fired product. Using the Microwave-Assisted Gas Firing technology (MAGF), simultaneous heating of the entire load ensures even heating at a much faster heating rate. For most products, this means shorter production time and significant energy savings. Objectives: the main objective was to reduce energy consumption for the drying and firing of brick, while the energy source is transformed from fossil fuels to electricity, and potentially from renewable energy. This was obtained by using new MAGF (microwave Assisted Gas Firing) technology. The goal was that the MAGF technology can be considered ready for implementation for the industry in general. Meaningful outcomes: benefits of such technology are:
   - Reduce firing time by up to 60%
   - Reduce energy consumption by up to 40%
   - Conversion to sustainable energy sources
   - Reduce CO_2 emissions by up to 60%
   - Improved product quality and reduced breakage due to lower temperature gradient

   The technology may be used for firing, drying, sintering and melting.
2. **TOREtech** (TOREtech, 2019). With TOREtech, a jet pump pure gas burner concept is being developed that functions without an external supply of combustion air. Pure gas burners only work with the hot furnace atmosphere already contained in the combustion chamber of the tunnel furnace and avoid the insertion of air, thus reducing the energy requirement. However, the pure gas burners currently available on the market do not have the required flame jet speed to achieve a homogeneous temperature distribution in the furnace, which means that burners with externally supplied combustion air have been used for tunnel furnaces up until now. This innovative concept combines the pure gas burner with a jet pump using natural gas. This approach has not yet appeared on the market and should increase the energy efficiency of the process. This innovative concept combines the pure gas burner with a jet pump using natural gas. This approach has not yet appeared on the market and should increase the energy efficiency of the process. Objectives: The new technology has the potential to reduce energy usage in tunnel furnaces in the medium term, thus securing cost benefits and competitive advantages. Wienerberger expects this gas burner innovation to demonstrate at least 10% more thermal efficiency and that it will therefore be possible to further reduce gas consumption and CO_2 emissions from the brick furnaces in a sustainable way. Meaningful outcomes: The development of the new technology is supported by numerical flow simulations and is currently being analyzed at two test stands. The “cold test stand” is being used to test the flow mechanics of the jet pump in the new burner concept and to validate and calibrate the CFD (Computation Fluid Dynamics) analyses. The “hot test stand” constitutes a section of a tunnel furnace. Here, the concept can be tested in a real, practical environment.
3. **CRAM** (CRAM, 2016-2019) project: Objectives: the aim is providing data and information toward an industrial strategy for ceramic raw materials in Europe. A dual approach, by fostering an interplay between the knowledge on mineral/waste potential and that on ceramic technology, is needed to go beyond running EU projects in this field. It can help drawing some of the innovation paths in the next decade. Expected results: 1) identification of critical situations in raw materials supply (CRMs list from the ceramic industry viewpoint); 2) study of the ceramic raw materials flow in Europe; 3)

technological classification of ceramic raw materials to support geological mapping and exploration; 4) industry-oriented definition of feasible alternatives (primary and secondary raw materials) to current key resources; 5) roadmap to new ceramic products and processes in function of the medium- to long-term availability of raw materials. Meaningful outcomes:

- Improving the knowledge on ceramic raw materials: addressing technological issues in the search for new sources and including opportunities from secondary raw materials.
- Linking legal definitions and commercial classifications to actual market and technological processes.
- Promoting a more efficient exploitation of known deposits: application of the full-exploitation concept to ceramic raw materials; drawing technological side-effects and possible hindrances in the ceramic production.
- Strengthening the value chain: mining > processing > ceramic manufacturing > recycling > public sectors > civil society, by fostering an interplay between the mining and ceramic sectors. Shedding light on the environmental and societal benefits from efficient exploitation and urban mining to supply economy (industrial production based in the EU and relative trades).
- Detailed knowledge of the raw materials flow in the ceramic sector. Mid-term and long-term scenarios for ceramic raw materials availability and demand with establishment of possible supply gaps. Application of the circular economy model to the ceramic industry.

4. **CCS4CER** (CCS4CER, PR-FESR;2021-2027) project focuses on ideating, simulating and demonstrating possible processes leading to a decarbonation of the ceramics industry, whose entire production line is proven to be massively energy demanding as well as a source of high amounts of CO_2 emissions. Objectives: the main goal is to identify the most efficient technologies for trapping and recycling carbon dioxide by performing material characterizations, process examinations and economic analyses. Simultaneously, an investigation on the mineralization of CO_2 will be conducted, starting from converted ceramic waste materials and formulating new mixtures for "carbon-negative" concrete and mortar. Meaningful outcomes: results include the release of a technical report outlining the developed technologies and applications, with a look to future implementations, as well as the promotion of the technological know-how transfer from research to industry (via publications, workshops, etc.).
5. **BLOCK4MAT** (BLOCK4MAT, PR-FESR;2021-2027) Objectives: the development of a prototype (platform) of blockchain technology applied to processes involving manufacturers of building materials, specifically ceramic tiles, brick products and composite materials. The prototype will be tested and validated on a laboratory and industrial scale, directly engaging companies in the sector, then combined with the BIM methodology and other digitization processes ongoing for building materials. Meaningful outcomes: the achievement of the expected results will promote optimization, traceability, and data security within the construction process, promoting and strengthening the competitiveness of the supply chain from design to dismantling of the work.
6. **ReWINDS** (ReWINDS:, PR-FESR; 2021-2027) project objectives respond to the construction supply chain's requirements to combine the needs of companies managing Construction and Demolition Waste and material producers seeking Secondary Raw

Materials to be integrated into their products in order to increase sustainability and normative conformity. Operational activities will be based on the testing of innovative formulations and technologies, laboratory validation of new materials, and quantitative demonstration of the degree of sustainability and associated emission reduction. Meaningful outcomes: the expected result includes the validation of the prototypes developed on pilot buildings, verifying their applicability, functionality and performance. The resulting technological improvement of the regional supply chain will be evaluated through the involvement of companies that will be able to capitalize on the results in their production process.

5.8.3 Projects which deal with Industrial Symbiosis and Energy Efficiency deeply involving the ceramics sector.

H2020 and Life projects related to IS and EE are, as follows:

1. **ATHOR** (ATHOR, 2017-2019) network was firstly dedicated to train researchers in multi engineering required fields for a better understanding of thermomechanical behavior of refractory linings used in I&S applications. Objectives: The project covered all the main features of thermomechanical analysis of refractory linings including material characterization, impact of corrosion on thermomechanical properties, thermal shock resistance, modelling of non-linear thermomechanical behaviors, instrumentation of industrial devices and measurement in operation conditions. The 15 ESRs recruited took advantage of the most sophisticated numerical tools to model, design and predict the life of different lining configurations in critical operational conditions. Being trained in scientific, technical and soft skills, these ESRs are the next generation of highly employable scientists and engineers in the refractory sector and related areas. Meaningful Outcomes: New testing methods and models have been developed to address the Scientific/Technological (S/T) challenges for these applications and help to design better performing refractory materials and linings. The research training has been implemented through strong relationships between academia and industrial partners across the EU. The ATHOR network is structured to take full advantage of intensive cooperation between academia (AGH, MUL, RWTH, UMINHO, UNILIM, and UORL), raw material suppliers (ALTEO, IMERYS), refractory producers (RHI MAGNESITA, PYROTEK, ST-GOBAIN) and consumers (TATASTEEL) with a direct link to the FIRE federation. This cross-disciplinary approach throughout the ATHOR value chain will dramatically increase the transfer of scientific knowledge to the refractory-consuming industries in the EU, ensuring their progress on social, environmental and economic aspects. The main scientific objective of the ATHOR network is to adapt and develop the most advanced modelling strategies and experimental technologies to the field of refractory to be able to perform reliable computations and measurement in the temperature range of the applications of these materials. ATHOR targets the development of high-end engineering technologies in the fields of material's science and numerical simulations to give a substantial contribution through the design of more robust and reliable refractory linings. Ultimately, it represents a reduction of the refractory costs, an increase of the equipment's availability and an enhanced process control. In addition to the great energy savings that meets the industrial partner's interests, the ATHOR project contributes also to tackling environmental issues.
2. **LIFEFOUNDRYTILE** (LIFEFOUNDRYTILE, 2015-2018), the main objective was to demonstrate the valorization of iron foundry sands and dust wastes in the ceramic tile

production process, thus contributing to the implementation of Waste Framework Directive (2008/98/EC) and the goals of the Roadmap for a Resource-Efficient Europe. France, Germany, Italy, Spain and Turkey generate around 4.1 million tonnes of iron foundry sands and dust wastes every year. In spite of the various treatments on the market, a high proportion of this waste ends up in landfill. In Spain, for example, an average of around 67% of waste by volume is land filled (2013). More valorization options for these materials are necessary in order to reduce the environmental impact of this type of waste. Objectives: The new applications will have three main benefits: the preservation of natural resources, the increase in foundry waste valorisation and environmental footprint reduction. The project will first obtain and characterize the samples according to various factors (i.e. mineralogical and chemical composition, moisture, etc.). It will then develop different treatment solutions (a total of 16 solutions combining six different by-products) according to the sample characteristics and the production requirements of four different ceramic tiles. The project will produce 60 tonnes of different ceramic tiles and test them according to different quality parameters (i.e. mechanical resistance, water absorption, etc.). The best performing prototypes (mixtures) will be used to produce a sample of 800 m^2 of wall tiles and porcelain tiles. The project results will be used to revise Best Available Techniques Reference Documents (BREFs) for both foundry and ceramic sectors (BREF codes SF and CER). Meaningful outcomes:

- Definition of an industrial process for the production of ceramic products from foundry dusts and sands, which reduces the consumption of raw material by 4.1% (translating to 366 000 tonnes in Spain);
- Creation of four small-scale prototypes of different ceramic applications and production of two batches of around 800 m^2 of wall tiles and porcelain tiles;
- Development of a database of foundry by-products information and acceptance criteria;
- Gathering of foundry waste characterisation data and definition of raw material (RM) requirements for different ceramic products; and
- The production of Environmental Economic and Human Health Risk viability assessments of the proposed solutions.

3. **LIFE SANITSER** (LIFE-SANITSER, 2013-2017) project Objectives: This project revised the production process in the Vitreous Sanitary Ware (VSW) ceramic sector by introducing relevant amounts of glass cullet waste from urban waste disposal in the ceramic blends for producing sanitaryware. The project focused process innovations designed to a) provide a sustainable management, in terms of recovery of large amounts of glass cullet waste (soda lime glass: SLG), b) improve environmental performances of the ceramic sector by reducing CO_2 emissions, c) enhance sustainability by energy saving and natural resources preservation. Meaningful outcomes, in VSW production no extensive use has hitherto been made of SLG, although its introduction would yield remarkable benefits. The replacement of feldspar-like materials (up to some 40-50%), or of flux agents(about 40-50 %), with SLG would provide: (i) savings in natural resources consumption (often imported because of increasing scarceness in European countries, implying also fuel consumption and emissions for transport); (ii) reductions of process energy consumption and CO_2 emissions. Introduction of SLG allows (a) to lower VSW production's firing temperatures from 1230-1250°C to1120-1150°C, and (b) to shrink soaking times by 20%. The related CO_2 emissions reduction will be quantified through the Life Cycle Assessment. All this can be realized by an

acceleration of main ceramic reaction kinetics exploiting the SLG high reactivity. The obstacles that hamper so far feldspars substitution with SLG are: 1. revision of firing time temperature cycles as a function of the new compositions with SLG; 2. proper management of the rheological behavior of slips bearing SLG, in order to avoid an excess of thixotropy which might result in a difficulty of casting; 3. deformations control of large ceramic output owed to pyro-plasticity effects; 4. revision of the glaze formulation, so as to have it matching the modified time-temperature cycles of firing and the new bulk compositions, and avoiding an increase of production costs.

4. **LIFECLAYGLASS** (LIFECLAYGLASS, 2013-2016) project Objectives: aimed to reduce the environmental impact of the ceramics sector by demonstrating the technical and economic feasibility of producing ceramic tiles using any type of recycled glass as a flux material. In doing so, the project hopes to reduce CO_2 emissions from the firing process and provide a commercial use for waste glass streams that are otherwise difficult to recycle. Like SANITSER project, LIFECLAYGLASS project deals both with IS and EE. The addition of the recycled glass to the mix will reduce the demand for new raw materials from natural resources. It will also reduce the required firing temperature from around 1250°C to around 1100°C, which will provide associated reduction in energy consumption and CO_2 emissions. The expected results have been the demonstration of a new stoneware production using recycled glass, leading to:
    a. the commercial use of difficult-to-recycle glass that is currently land-filled;
    b. reduced demand for natural resources in clay tile production;
    c. energy savings of 10-15%;
    d. a reduction of about 2 000 t of CO_2 emissions per year for a medium-size;
    e. factory (brick production capacity of 300 t per day);
    f. a reduction in the cost of producing clay tiles.

5. **AMITIE** (AMITIE, 2017-2021) is an ongoing project which will promote fast technology transfer and enable as well training of Additive Manufacturing (AM) experts from upstream research down to more technical issues. Additive manufacturing (AM) technologies and overall numerical fabrication methods have been recognized by stakeholders as the next industrial revolution bringing customers' needs and suppliers' offers closer. It cannot be dissociated to the present trends in increased virtualization, cloud approaches and collaborative developments (i.e. sharing of resources). AM is likely to be one good option paving the way to Europe re-industrialization and increased competitiveness. AMITIE will reinforce European capacities in the AM field applied to ceramic-based products. Objectives: Through its extensive programme of transnational and intersectoral secondments, AMITIE will promote fast technology transfer and enable as well training of AM experts from upstream research down to more technical issues. This will provide Europe with specialists of generic skills having a great potential of knowledge-based careers considering present growing needs for AM industry development. To do that, AMITIE brings together leading academic and industrial European players in the fields of materials science/processes, materials characterizations, AM technologies and associated numerical simulations, applied to the fabrication of functional and/or structural ceramic-based materials for energy/transport, and ICTs applications, as well as biomaterials. Meaningful Outcomes: Those players will develop a new concept of smart factory for the future based on 3D AM technologies (i.e. powder bed methods, robocasting, inkjet printing, stereolithography, etc.) and their possible hybridization together or with subtractive technologies (e.g. laser machining). It will allow for the production of parts whose dimensions, shapes, functionality and assembly

strategies may be tailored to address today's key technological issues of the fabrication of high added value objects following a fully-combinatorial route. This is expected to lead to a new paradigm for production of multiscale, multimaterial and multifunctional components and systems.

6. In the **FERTILIFE** (FERTILIFE, 2015-2018) project, waste gases from the ceramic industry will be used in agriculture as an acidifier in irrigation water. Objectives: This project aimed to develop a prototype in which CO_2 emissions from a ceramics factory will be captured and used to carbonate water that will be used to irrigate crops. Meaningful Outcomes: The project will:
   - Demonstrate the feasibility of "carbonic fertigation" – the injection of carbon into an irrigation system for citrus crops, and analyse the impact of the continued use of CO_2 in the soil and plant irrigation network.
   - Design and implement techniques for proper CO_2 dissolution in a drip irrigation system, and monitor the implementation of the system and its deployment on different plots.
   - Assess the impact of carbonic fertigation on root respiration, and thus on total soil organic matter content.
   - Quantify the impact of carbonic fertigation on the use of chelates and other fertilisers. The use of chelates (chemical compounds) in agriculture is necessary to help plants absorb trace elements such as iron from soils with high pH, as in the Mediterranean basin.
7. **WINCER** (WINCER, 2015-2017) project aimed to develop innovative ceramic tiles made from over 70% recycled materials from urban and industrial wastes in substitution of natural raw materials. The project aimed to recover soda lime glass cullet waste that is not currently being reused or recycled as glassware. This is expected to result in improved environmental performance by reducing the use of raw materials and reducing the maximum sintering temperature. These two changes are associated with reduced energy consumption and associated greenhouse gas emissions. Objectives: The specific objectives were related to:
   - contribution to sustainable waste management by recovery of the amount of soda lime glass cullet waste that today is not re-introduced in glassware (about 30% of the total glass waste);
   - reduction of the use of natural resources thanks to: the use of soda lime glass, coming from urban collection and the reuse of green scrap tiles, generated during the industrial process;
   - improvement of the environmental performances of the ceramic tiles sector by reducing CO_2 emissions, energy consumption and methane use.

   The combination of these different wastes enables the production of innovative ceramic tiles with similar or improved mechanical properties respect to the traditional ones. The productive cycle is similar apart two main innovation aspects concerning the body mix preparation (over 70wt% of recycled wastes in substitution of natural raw materials) and the firing cycle (maximum sintering temperature reduced.

8. **5REFRACT** (5REFRACT, 2018-2020) is a project which deals with Industrial Symbiosis and Energy Efficiency. Refractories are used in high temperature processes, involving raw

materials that are largely considered as "critical". Surprisingly, only 7% of the raw material volume arises from recycled sources. While it could be expected that the "4R" approach (reduce-reuse-remanufacture-recycle) is well established in steel companies, valorisation of refractory materials is most often sporadic and the sector's Best Available Techniques reference document (BREF) only provides general recommendations in this respect. Objectives: its specific objectives are the following:

g. Development of new high added-value refractory materials that will be up to 70% reprocessed material from spent refractories.
h. Reduction of soil occupation and pollution by avoiding the landfilling of up to 3,600 tonnes of refractory waste.
i. Reduction of CO_2 emissions (3,340 tonnes CO2/year) and energy consumption (approx. 6,100,000 kWh/year) by recycling refractories, as it is not necessary to produce magnesite and alumina from the source mineral.
j. Establishment of guidelines for the European steel sector to adopt these strategies, disseminating the good practices defined in the sector.
k. Contribution to the state-of-the-art in refractory waste management so as to enrich and complete the BREF document on steel with specific methodologies and applications.
l. Analysis of synergies between the steel industry and other energy-intensive industries in order to define new circular economy models based on the sharing and use of resources.

Meaningful Outcomes: The overall purpose of the LIFE 5ReFRACT project is to extend the "4R" approach to a "5R"paradigm (reduce-reuse- remanufacture-recycle-re-educate) and apply it to the steel sector and refractories market, thus achieving an integral valorisation of refractory materials (the aim is to increase the recovery of refractories up to 80% of the recoverable fraction). The LIFE 5REFRACT project will constitute the first industrial and systematic demonstration experience dealing with refractory waste in the steel sector.

9. **LIFECERSUDS** (LIFECERSUDS, 2016-2019) project. A combined sewer is one that collects surface runoff in addition to industrial and domestic wastewater. Widely found throughout Europe, this type of sewer can overflow, creating a challenge for meeting the water quality goals of EU legislation, including those of the Urban Waste Water Treatment Directive and the Water Framework Directive. Surface water drainage in dry areas of Spain has been overlooked and considered a secondary component of combined sewers, rarely relevant except during periods of torrential rainfall. This attitude, along with rain patterns which differ greatly from those in countries where the principles of sustainable drainage have been widely implemented, might partly explain the relative lack of SUDS in Spain. SUDS involve a range of structural components (ponds, basins, swales, infiltration systems) and non-structural responses (cleaning programs, amended regulations) designed to ameliorate the otherwise degrading effects of older, conventional drainage systems. One of the EUs priorities is to adapt urban areas to climate change by using green infrastructure, such as SUDS (EEA Technical report No 15/2011 - Green infrastructure and territorial cohesion). Furthermore, it is clear that such solutions provide additional benefits such as ecosystem services. Objectives: improve the resilience of cities to climate change and promote the use of green infrastructure in their urban planning as a means of managing surface water flooding. It aimed to achieve this goal through the development and implementation of a demonstration low-carbon SUDS. The system would consist of an innovative permeable surface with

a very low environmental impact, based on the use of tiles with low commercial value. Specifically, the project aimed to:

m. Reduce flooding caused by torrential rain by increasing the number of permeable surfaces in cities;
n. Re-use water stored during the rainy season for use during periods of drought;
o. Reduce runoff volumes and peak flows to treatment plants and receiving water bodies;
p. Integrate treatment of rainwater into the urban landscape;
q. Protect water quality by reducing the effects of diffuse pollution and thus avoiding problems in sewage treatment plants;
r. Reduce CO_2 emissions linked with the manufacture of pavements for SUDS, given that the project will use ceramic materials with low commercial value, giving ceramic tile manufacturers a new revenue stream;
s. Provide an aesthetic SUDS and prevent ponding, increasing the comfort and safety of streets in rainy weather;
t. Develop a ceramic SUDS with greater environmental efficiency;
u. Demonstrate that this ceramic SUDS is suitable for rehabilitating urban areas with light traffic and to enable better management of rainwater in areas with particular geo-economic conditions;
v. Guarantee transferability beyond the end of the project through training activities and a business plan aimed at engineers, architects and companies, and by increasing local authorities awareness; Generate precise technical documentation to facilitate replication in other cities based on the principles of the LIFE CERSUDS demonstrator.

Meaningful Outcomes: The **LIFECERSUDS** project successfully designed and produced a ceramic tiled pavement in the Spanish city of Benicssim, highlighting numerous environmental benefits throughout the application and use of this innovative low carbon permeable surface that manages surface water flooding. During the project, the system received more than 1 000 m^3 of rainfall, from which 86% was managed by the system, either through collection for future use (7.8%), infiltration in the ground or evaporation into the atmosphere (78.2%).

10. **REDUCER** (REDUCER, 2012-2014) project Objectives: aimed to reduce energy consumption in ceramic dryers and kilns by optimising process variables and reusing waste heat from kilns in dryers. Meaningful outcomes: Environmental: energy savings and reducing CO_2 emissions by 1,492 tCO_2/year after implementing not only several energy-saving actions, but also the best practices related to energy consumption in industrial facilities were the main obtained results. Economic: energy savings amounted to 6.9 GWh/year. Technical: This technology can be generally implemented in those sectors and industries with surplus heat in one facility and heat demand in another.
11. **HEROTILE** (HEROTILE, LIFE; 2015-2019) LIFE HEROTILE Project developed: - two new types of roof tiles (Marseillaise and Portuguese tiles) with a shape characterized by a higher air permeability through the overlap of the tiles, and then a better energy performance by passive disposal of the solar radiation through under-tile ventilation; - a practical and simplified free-license software for architects and technicians – SENSAPIRO Software ENergyYES SAvings PItched Roofs- that, as developed on the basis of experimental data, it will be able to predict the energy performance of the same building in changing only the roof configuration. Objectives: To help the EU construction

sector (refurbishment and new constructions) achieve its energy efficiency targets and related CO2 emissions and facilitate the global market uptake of an eco-innovative EU product able to help reaching these objectives.

12. **REMEB** (REMEB, H2020-EU.3.5.4. H2020-WATER-2014-two-stage - Grant agreement ID: 641998; 2015-2018) "Eco-friendly ceramic Membrane Bioreactor (MBR) based on recycled agricultural and industrial wastes for waste water reuse". Currently available MBRs using inorganic membranes tend to have high running and maintenance costs. The REMEB project proposes to develop a new type of MBR which will significantly decrease the cost of MBR technology. REMEB will use byproducts from agro-industrial wastes (e.g. olive stones, hazelnut shells) and ceramic waste (chamotte) to develop the MBRs. Objectives: The REMEB project brings together 11 partners from seven different countries The main objective of the REMEB project is the implementation and validation of a low cost recycled ceramic membrane bioreactor (MBR) for water reuse in municipal and industrial wastewater treatment plants. Meaningful outcomes: The REMEB project has partners in three countries: Spain, Italy and Turkey. The first stage of the project is taking place in Spain using chamotte, olive stones and waste from marble shaping and polishing. The membrane will then be replicated in Turkey and Italy using recycled materials and wastes that are available locally. Validation of the technology will take place at a wastewater treatment plant in Aledo in the Murcia region of Spain, with the aim of using the water for irrigation purposes in this water scarce area.
13. **CLEANTECHBLOCK2** (CLEANTECHBLOCK2, H2020-EU.3.5. H2020-EU.2.3.1; H2020-SMEINST-2-2016-2017 - Grant agreement ID: 766614; 2017-2019) project is a project that is led by Gråsten Brickworks in Denmark to pursue an innovative building component that will create a systemic change with the construction market and recycling market in Europe. The project follows on from where the project CleanTechBlock left off, and aims to finalize the technical development that started under CleanTechBlock. The intention is to then commercialize this product which is a patented multifunctional sandwich-block based on the combination of two clay brick shells and foamed recycled glass . It is hoped that this newbuilding product will meet the market preferences for more environmentally friendly products, as well as make a positive contribution to the energy efficiency of buildings, while reducing the demand for raw materials. Objectives: Clay bricks are one of the preferred building materials in Europe, but they are facing numerous threats due tightened regulations on buildings' energy and raw material consumption levels and CO2 emissions. These threats together with market trends such as increasing environmental conscience, preference for green materials and an excellent clay bricks' public image creates a major market opportunity that Gråsten Brickworks (GB) aims to pursuit through the development of an innovative building component which will enable a paradigm change within the construction market and recycling in Europe. GB vision is to take the final steps of commercial and technical development and product maturation towards the commercialization of CleanTechBlock (CTB) – a patented multifunctional sandwich-block based on the combination of two clay brick shells and foamed recycled glass. CTB's advantages over bricks are compelling as the insulation, strength properties and construction price are similar and it offers: an overall increase in the living area (3-5%), a reduction in the overall house wall construction time (5x faster), while reducing maintenance requirements and transportation costs. It also contributes to the mitigation of environmental problems due to an increase of glass waste recycling, decrease of raw material (clay) and energy consumption and CO2 emissions. Meaningful outcomes: the project has demonstrated

value for money and reduced labour time in the construction phase, on top of reduced transportation costs. As well as this, the sandwich-blocks offer an overall increase in the living areas of 3-5%, while also demonstrating compelling insulation properties. CLEANTECHBLOCK2 is expected to result in an expected sales turnover of €67M and profits of €15M, 6 years after commercialization. The product is expected to be sold for both residential and non-residential construction and the primary target markets will be Denmark, Sweden and Germany. The CLEANTECHBLOCK2 project will help the EU to achieve its energy and environmental policy objectives.

14. **DESTINY** (DESTINY, Horizon 2020 - SPIRE Grant agreement No 820783; 2018-2022) "Development of an Efficient Microwave System for Material Transformation In Energy Intensive Processes for an Improved Yield" project aims to realize a functional, green and energy saving, scalable and replicable solution, employing microwave energy for continuous material processing in energy intensive industries. The target is to develop and demonstrate a new concept of firing for granular feedstock to realize material transformation using full microwave heating as alternative energy source and complement to the existing conventional production. The DESTINY system is conceived as cellular kilns in a mobile modular plant with significant advantages in terms of resource and energy efficiency, flexibility, replicability, scalability and a reduced environmental footprint. Objectives: The DESTINY project aspires to introduce a "first-of-a-kind" high temperature microwave processing system at industrial level offering a variety of vital benefits to energy intensive sectors: reduced energy consumption, lower lifetime operating costs and enhanced sustainability profile. The DESTINY system is conceived as cellular kilns in a mobile modular plant designed to cover the "material feedstock-firing-product storage" process in a unique clean system with increased production flexibility. Working with throughputs ranging from 10% to 100% capacity should be enabled without any major loss of the overall process performance. Objectives focus towards the improvement of efficiency ratios in the following areas: Flexibility of ±30% to energy input within RES (Renewable Energy Sources) fluctuations time frames without significant losses in specific energy efficiency; Improvement in energy efficiency of 40% (depending on different industry and product applications); Improvement in terms of resource (fuel) efficiency exceeding the value of 40%; Decrease in CO_2 emissions by 45% (without considering the electricity generation at steady state); Decreased OPEX and CAPEX by 15%. Meaningful outcomes: the influence of the DESTINY solutions in terms of stability, process efficiency and characteristics of raw materials, intermediate/sub/final products will be investigated to improve performance of the industrial processes within 3 industrial sectors (Cement, Ceramics and Steel). New heating technologies, monitoring systems and numerical simulation tools will be used to drive the design and to excel in the outcome. The industrialization and sustainability of DESTINY high temperature microwave technology will be assessed through the evaluation of relevant key performance indicators (KPI) with life cycle methodologies. With the final aim of ensuring a large exploitation and market penetration for DESTINY, technology-based solution business models, economic viability and replicability analysis will be conducted. For guaranteeing industrial transferability, appropriate exploitation and dissemination activities have been defined during and even after the end of the project.
15. **FORGE** (FORGE, H2020; 2020-2024) "Development of novel and cost-effective coatings for high-energy processing applications". The equipment used in energy-intensive industries is pushed to the limit, but improvement of current and future equipment is

essential to increase production efficiency, component lifetime and reduce environmental impact. Innovation of the materials is the key. Objectives: the project will develop novel coatings of compositionally complex alloys and ceramics, combining machine learning models, thermodynamic calculations, and high-throughput experiments. Meaningful outcomes: FORGE will demonstrate these coatings on processes such as CO2-capture, waste heat recovery, components undergoing wear and in kilns, defying the acting degradation forces, and assuring coating effectiveness with smart monitoring of their deterioration. FORGE aims to minimise the overall capital and operative expenses especially in steelmaking, aluminium, ceramic tiles and cement industries.

16. **NEWSKIN** (NEWSKIN, H2020; 2020-2024) project aims to create an Open Innovation Test Bed (OITB) to provide the Innovation Ecosystem (IE) with the necessary technologies, resources and services to uptake a set of game changing, efficient and cost-effective innovative processes to manufacture nano-enabled industrial and consumer products as well as the necessary testing capabilities to demonstrate nano-enhanced goods features. Objectives: the overall project is divided in 9 Work Packages. The first 4 Work Packages aim to create the OITB structure, upgrade the different facilities integrated within the NewSkin OITB, calibrate these upgraded facilities and create a Catalogue of Services and a Value Proposition. WP 5 and 6 aim to validate the OITB members coordinated services provision. WP7 will include the development of the on-line platform, after which the Consortium will start the Innovation Ecosystem Engagement activity to connect the OITB with the target markets and stakeholders. Wp8 will include the Dissemination and Exploitation activities to ensure the OITB sustainability after the Grant Execution including the preparation of events, Technology Roadmaps and the OITB Marketing and Business Plan that will role the OITB activity after the Grant Execution. WP9 will be devoted to the Project Management Activities.
17. **ASTRABAT** (ASTRABAT, H2020; 2020-2023) aims to develop optimal Lithium-ion battery solutions for the increasing demands of the electric vehicle market in particular. Objectives: the goal is to fulfil Europe's need for a safe, high-energy, sustainable and marketable battery for green mobility that could be manufactured in Europe on a massive scale. Meaningful outcomes: ASTRABAT is part of a broader drive by the European Union to make electric mobility become the next transport mode and contribute to the EU overall goal to reduce GHG emissions by 80-95% by 2050 (currently, the transport sector is responsible for around one quarter of Europe's GHG emissions). It is expected that e-mobility will represent 70% of the total rechargeable Li-ion battery cell market's value in 2022 and that 70% of the EU electricity should be produced by renewable energies. Hence, the electric battery storage is vital in this transition to clean mobility and clean energy systems.
18. **LIFE HYPOBRICK** (HYPOBRICK, LIFE18 CCM/ES/001114; 2019-2022)**.** The manufacture of ceramic materials is energy intensive, consumes large amounts of primary raw materials, and produces considerable amounts of GHG. Bricks and roof-tiles are the ceramic products with the highest GHG emissions. Objectives: the project aims to demonstrate the feasibility of manufacturing waste-based building products using an extremely low CO2 emission process, called the alkalineactivation process (AAP). The project will focus on manufacturing bricks made from the new waste-based material in southern and northern European countries (Spain and Germany), in which the wastes available and the constructive requirements are quite different and cover the trends existing in a significant number of European countries. Meaningful outcomes: the project will: formulate waste-based mixtures and produce new materials for manufacturing bricks using the AAP that meet all the technical and environmental requirements for

international standards and for the market; define the operating variables of all the process stages involved in the AAP; modify the industrial facilities to allow the manufacturing of the new building material; solve the potential production problems that may arise during the pilot and industrial trials in order to obtain building products free of defects and with the required properties; obtain a cost-effective and economically-viable building material with an innovative process that favours its commercialisation; and make an agreement with another manufacturing company (outside of the project consortium) to replicate and transfer the results before the end of the project.

19. **CIRCULARCARBON** (CIRCULARCARBON, 2021- ongoing). The CIRCULARCARBON project was born with a demonstrative objective that exemplifies a circular economy concept based on innovative technologies aimed at promoting the energy transition and the decarbonisation of the economy within the industrial fabric of the Valencian Community. Specifically, it is a demonstrator that allows the use of abundant waste in the Valencian Community for the production of a value-added product such as activated carbon and its application in key devices in the energy transition, such as energy storage systems. (batteries) and the improvement of the environment through water and gas treatment processes. Objectives: On the other hand, the energy concept is integrated as a fundamental and transversal pillar to the entire process of life cycle analysis (LCA) of the project, since energy is analyzed from its inclusion in the system (clean generation and storage) to the generation of storage systems (battery demonstrator) that would close a sustainable cycle. Therefore, the project consists of 3 Demonstrators: one for the generation of activated carbon from waste and another two to be applied in energy storage systems and in environmental uses.
20. **Ecocerâmica e Cristalaria de Portugal** (ECP, PRR; 2022-2025). Increase the competitiveness of national ceramics and domestic glassware, based on factors of innovation, differentiation and a strong collaborative dynamic and investment in innovation throughout the years various segments of the sector's value chain, supported by improving the qualification of its assets. The ECP-Pact participant and activities structure, configures a complete consortium, as it brings together industrial productive and R&Di capabilities, that will cover all productive advances, and technical-scientific developments foreseen in the ECP-Pact project. Objectives: Ecocerâmica e Cristalaria de Portugal Agenda´s aims to strengthen the competitiveness of the ceramics and crystal industries at national level, based on factors of innovation, differentiation and a solid collaborative dynamic, with investments in all stages of the sector's value chain and sustained by improving the qualifications of its assets.

5.9 Major conclusions on Energy Efficiency findings across sectors

The analysis carried out on the Energy Efficiency section has highlighted the improvement of solutions for the reduction of energy utilization and environmental impact, and cost savings. Case studies and projects have been shown the methods for energy analysis and optimization, by analysing the suitability for energy strategies within Energy Intensive sectors.

As sources of energy losses considered as a waste for a company could be a valuable resource for another one, it is important to identify and to implement the use of techniques and technologies for the production, use and recovery of energy. Synergies among companies can lead to the optimization of energy consumption and common production to reduce the use of fossil fuels and, consequently, the carbon footprint of industry as well as the investment, maintenance, and management costs of the energy infrastructure.

It has been shown in some cases, such as the steel sector, the reduction of product life cycle energy use and emissions by improving product design, recovery and reuse, remanufacturing and recycling. The cooperation among different industrial sectors can help overcome the lack of technical knowledge regarding low carbon and renewable technologies as well as cost savings. In addition, the main challenges identified by this analysis has highlighted further improvement in energy efficiency. For instance, in the steel sector, best available steelmaking processes have optimised energy use. In the future, energy efficiency improvements in Energy Intensive sectors are expected through technology transfer and by applying best available technology. In addition, a suitable energy system model should include the following features: multi-objective optimization, in order to facilitate minimisation of both costs and carbon emissions; the technology description at unit level; sufficient temporal detail, showing energy demand; energy storage technologies and flexible energy demands; the system superstructure, enabling the introduction of energy service demand or energy production technology.

Going into more details, some results on Cross sectoral aspects of EE, can be summarized as follows:

- Synergies among companies to optimize energy consumption and common production to reduce the use of fossil fuels and the carbon footprint of industry, the investment, maintenance, and management costs of the energy infrastructure;
- Identification and implementation of techniques and technologies for the production, use and recovery of energy, particularly energy losses (considered as a waste for a company but a valuable resource for another one);
- Technology transfer and application of the best available technologies;
- Digitalisation and introduction of measures to favor energy efficiency;
- Implementation of new technological solutions for plant and process optimization;
- Integrated control system of the process steps, supported by artificial intelligence;
- Measurement of the energy consumption of single units and equipment for optimization;
- Preventive maintenance;
- Systems for energy recovery (e.g. from exhaust gas);
- Low temperature waste heat recovery for power generation;
- Replicable instruments for energy cooperation;
- Business models for joint contacting of energy services for industrial parks;
- Drafts amendments to existing regional/national/EU policies and legal frameworks to simplify energy cooperation/services at all governance levels.

In the context of EEIs, new and innovative technologies, such as advanced materials, smart sensors, and automation, will provide new tools and processes that can drastically improve EE. In particular, the integration of these technologies into industrial processes unlock further efficiencies and set new benchmarks for energy consumption. Finally, the confluence of technological, policy, and market forces can accelerate the transition to the improvement of EE. The future of EIIs will be characterized by its ability to adapt, innovate, and integrate EE into their industrial operations, ensuring its role in the future sustainable economies.

6 Effects of Industrial Symbiosis and Energy Efficiency on the workforce

6.1 Introduction

In the context of carbon neutrality targets, realising the symbiotic development of traditional energy industries and new energy industries is the key aspect in order to reduce CO_2 emissions and achieving the zero-carbon target, according to the European Green Deal and Paris Agreement. At the same time, it is important to ensure the economic benefits of IS. Within this context, the support of governments to promote IS and EE in the next few decades will be crucial. In addition, establishing new connections between EIIs will address the mutually beneficial symbiosis in the industry and support the growth of IS and EE achievements (Qiu, Zhao, Wu, & Ren, 2024). In order to implement IS and EE in the European EIIs is crucial to take into account the skills shortages in these sectors and to provide tools for the future job profiles. This is due to the necessity to update qualifications, knowledge and skills that can support cross-sectoral and IS activities. In order to meet the demands of the future in terms of the skills needed, it is crucial to identify current and future skill needs for the selected job profiles. A recent work provides a tool for users, such as educational institutions, to help them teach in ways that best align with the skills needed by their students in the future (Goti, et al., 2023). Furthermore, the current digital transformation can lead to increase the requirement for a highly qualified, specialized, multi-disciplinary and multi-skilled workforce. Digital skills are fundamental for implementing a pro-active skills strategy based on IS and Energy Efficiency in different sectors. In addition, over the last few decades, the importance of building Science, Technology, Engineering, and Math (STEM) skills to develop the workforce of the future have been increased. On the other hand, the importance of 'soft skills', including collaboration, teaming, ethical judgement, and communication has been emphasized (Rotatori, 2020).

In the National Energy and Climate Plan (NECP) occupation changes in the near future are highlighted (European Commission, 2019), emphasising the need of new jobs in the renewable sector and in the fossil fuels sector and new skills in EIIs in order to achieve the carbon neutral by 2050 and the zero-pollution goal (European Commission, 2019). In this context, the workforce should be up-skilling and reskilling for the energy transition into their National Recovery and Resilience Plans. For this reason, in the next few years, the increase of job, the attraction of young talents, the development of new business lines and higher workload are expected (Branca T. A., et al., 2021). Although skill demands are present in any category of workers, skill needs should be mostly included specific job-related skills, digital, green and personal skills, and regulatory and entrepreneurship skills. In addition, attracting and retaining talented people will be crucial to the sustainability and competitiveness achievements in EEIs. Continuous re-skilling and up-skilling of the workforce is addressing the current skills needs in order to obtain a workforce with updated skills to be adapted to digital and green transformation and novel working systems. Through a long-term methodology the skills gap between the industry expectations and the current workforce can be reduced, and also can provide tools for the recruitment of new talents, and introduce education and training programs. In this regard, the concept of continuous and lifelong learning is crucial for employees, who will need to respond to new concepts and production changes (Akyazi T. , et al., 2024).

In industries and activities that aim at improving environmental and socioeconomic conditions, green economic development aims to combine economic, social, and environmental agendas

(Yeung, 2013). Moving towards a greener economy can create opportunities for new technologies, investment, and jobs. The Green Jobs Report estimated that efforts to meet climate change can result in the creation of new "green jobs" in the coming decades (UNEP, 2008). A recent research, carried out by Cedefop on the six EU countries (Cedefop, 2010) has showed that skill shortages already constrain the transition to a greener economy and it has also documented the need of new skills. On this subject, some countries are developing innovative strategies to address emerging skill needs while others adjust existing mechanisms and systems on a more ad-hoc basis. In particular, skills development systems should go beyond matching training to labour market needs but, they need to play a catalytic role in the future economic growth and resilience in order to take advantage of opportunities and to mitigate the negative impact of change. In particular, establishing a sectoral skills strategy, defining the foreseen skills requirements, identifying the skills mismatch between the job profiles and the labour force, developing continuous training programs, reskilling and upskilling of the workforce through well-developed training programs, represent the most important actions for achieving a high-qualified workforce (Akyazi, et al., 2020).

In this context, integrating sustainable development and environmental awareness into education and training can contribute to change the consumer behaviour and triggering market forces towards the greening agenda ahead. This transformation can affect skill needs in three ways:

1. the green transformation shifts industrial activities towards those that are more efficient and less polluting. This process, leading to structural shifts in economic activity, and, consequently, in employment, between and within industries, is called green restructuring.
2. structural changes, new regulations, and the development of new technologies and practices result in the emergence of some entirely new occupations. These will need the provision of relevant training courses and the adjustment of qualification and training systems.
3. new skills will be needed by workers in many existing occupations and industries in the process of greening existing jobs. This will require a major effort to revise existing curricula, qualification standards and training programs of education and training.

The transition to a greener economy presents a high employment potential in the long term, through the creation of large jobs both directly and indirectly through supply chains. However, in this context, skill shortages represent a major barrier to transitions to green economies and the creation of green jobs, and this will increase in the future. Skill shortages for green jobs are due to different factors, including underestimated growth of certain green sectors, a general shortage of scientists and engineers, the low attractiveness of Energy Intensive Industry for young people, the general structure and shortages of teachers and trainers in environmental awareness topics and in green sectors (e.g. renewable energy, energy efficiency). Furthermore, the lack of policy coordination represents a further specific issue. In this regard, a holistic approach aims at handling sustainability barriers in the present business environment to ensure the sustainability of CE and Industry 4.0 operations (Kumar, Singh, & Kumar, 2021). In this context, the lack of skilled workforce, ineffective performance framework and short-term goals of an organization represent major barriers, due to the lack of skills related to Industry 4.0 technologies and CE activities. For this reason, it is important to develop an effective and integrated strategic approach. On the other hand, barriers and benefits in developing and updating curriculum related to EE have been identified (Desha & Hargroves, 2014). On this subject, a strong policy support is required to share the technological and economic risks, and to carefully consider workforce upskilling and recruitment of new talents (Akyazi, Oyarbide, Goti,

Gaviria, & Bayon, 2020). In this context, it is crucial adding the Industry 5.0 perspective (human-centric, resilient, sustainable) to Industry 4.0, followed by an Industry 5.0 framework for engaging stakeholders, raising awareness, increasing acceptance, gathering and exchanging good practices, enabling policy and regulations, market conditions, development indicators, and others (Schröder, Cuypers, & Gotting, 2024). This should also include a long-term management of the European Industry workforce and skills needs to build a human-centric European Industry. The social practices and cooperation of companies and the education system will aim to adjust skills linked with the industry demands, related to Industry 5.0, providing advantages not only for workers but also for companies, providing benefits for their competitiveness (Branca T. A., Colla, Murri, & Schröder, 2024). An ecosystem-oriented alliance will integrate not only competences and expertise but also the possibilities and responsibilities of stakeholders related to industry, policy, research and education and civil society.
In coming years, attracting and engaging young talents should be a priority in order to enforce competitiveness and to develop a cross-sectorial cooperation to achieve energy and resource efficiency. Particularly in some sectors the increasing rate of change in skills needs requires updating the skills, not only by national responses but also by flexible and dynamic action at sector and local and regional levels. For this reason, skills developments should be anticipated by performing essential activities, such as: securing talents; training needs to address transversal skills; supporting of governments to a green and just transition; close collaboration with universities and research centres; increasing investments in training on environmental awareness; improving social dialogue; setting channels for workers to report their training needs and concerns; anticipating changes involving governments, companies and regional authorities (Antonazzo, Stroud, Weinel, Dearden, & Mowbray, 2021).

On this subject, the role of education and training policies in low-carbon strategies is fundamental in order to meet the skills needs, and to overcome skills gaps (Ranieri, 2013). By developing suitable formation and training paths, focused on a multidisciplinary approach, mainly based on green and digital skills, a new skilled workforce can manage the complexity of cross-sectorial cooperation in the context of IS and Energy Efficiency. This is important in shaping VET system responses to cope with the transition. In particular, VET must continuously respond to economic changes and to the transition to a low-carbon economy, taking into account that the whole economy is affected.

6.2 The workforce in Industrial Symbiosis

Over the last few years, in order to clarify the mechanisms of policy intervention and facilitation of IS, some studies have been focused on how policy is conceptualized and studied. It has been shown that a dynamic process perspective is important to reveal the actual mechanisms through which policy intervention and facilitation affect the evolution of IS. In particular, the key aspect is to identify the sequence of events connecting policy process and IS practices (Jiao, 2014).

When the IS is promoted and implemented, generally the industrial priorities are sustainability, cost reduction and economic competition. In particular, the higher emphasis is put on environmental impact then on potential job opportunities/creation.

Among the different goals of Industrial Symbiosis (International Synergies 1) (International Synergies 2), the Sustainable Development Goal 8 (Decent work and economic growth) is

“Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all”.

The social dimension of IS projects requires working with the organizational culture, which will affect the strategic management, the staff management model and the organizational structure. For instance, Corporate Social Responsibility or Human Resources policies represent key factors for the viability of any technological innovation or production model. On this subject, it is strategic to consider the new organizational forms, new models of leadership and staff management for the activity with people (develop knowledge, new skills, aptitudes and attitudes). Consequently, companies should identify the required professional profiles, skills and competences that need to be attracted for new business models and methodologies, such as IS models (Courtois, 2017). In addition, the organization and the strategy of companies are transforming, due to globalization, information and communication technology (ICT), and new demand. And this new model needs new values (cooperation, equal opportunities, transparency, creativity, solidarity, tolerance, etc.) and, consequently, new corporative competences such as communication, teamwork, innovation, adaptability, social abilities, stress and emotion management, willingness to learn, etc.

In order to implement IS, the traditional company organisation could need to be modified. In particular, the transition to a circular economy needs to accept and adopt the principles of circular economy throughout the entire company and a change of attitude is necessary on different levels:

- Strategic: openness to participate in a multi-stakeholders approach, flexibility and creativity.
- Financial: creation of new funding opportunities for new business models and innovative projects.
- Legal: different and flexible approach to overcome legal barriers for new business models and cooperation agreements.
- Commercial: engaging in circular economy offers companies new selling opportunities.

In addition, to implement the synergies related to IS, new **skills/competences** could be taken into account. Although some specific skills depend on symbiosis projects and on the sector, some key competences are necessary for all levels. In particular, the following skills/competences can be transversal to all sectors:

- Openness for information sharing.
- Co-creation and cooperation to involve different stakeholders.
- Knowledge on the composition and development of products. This is important for developing innovative products based on secondary raw materials, residual waste or recycled materials.
- Managing a diversity of tasks.
- Applying innovative management tools to make the transition to circular economy.

As in some IS implementations is often necessary to add intermediate waste/resource processing or treatment steps, more workforce can be required leading in turn to **increase employment**. On the other hand, the cooperation between sectors can produce an impact on existing jobs, that will become more complex, involve more cooperation and co-creation. On this subject, new job can be expected in design, innovation and product development, disassembling, administrative handling of new service contracts, resource scout, information manager.

Due to the need to coordinate an IS project an **implementing agency/facilitator/Independent matchmaking institute** is often a key actor for this task in order to implement possible synergies. Although the coordinator could be either public or private, it is important that the facilitator can act autonomously and independently. The IS facilitators could be helped with incentives, political support and stakeholder's engagement. The **role** of an IS facilitator is seen as a **'swiss knife' profile**, consisting in providing **knowledge** (tools, methodology), to be able to **foster trust** between stakeholders and to perform in-depth analysis of flows.

Different skills, competences and knowledge are important for the of IS facilitator profile. Based on the work carried out in the INSIGHT project (INSIGHT) **skills**, **competences** and **roles** required to implement IS have been identified. In particular, the expected role of the IS facilitator concerns the facilitation and the collaboration among different stakeholders of an IS as well as the stakeholders engagement. In addition, providing knowledge (tools, methodology), analysis of the industrial ecosystem, management and coordination, represents the further task required for facilitators. In general, an IS facilitator should have multiple tasks and skills, making his role evolving over time. In addition, the competences integrated in a team can respond to different levels of requirements. The required skills of an IS facilitator concern transversal technical skills and knowledge. In addition, the role of facilitator as a bridge between the different stakeholders requires soft skills and networking skills. Going into details, the identified skills of facilitator (INSIGHT) are, as follows:

Networking – Collaboration facilitation.

The cooperation and commitment of stakeholders is essential to develop and maintain strong relationships with companies as well as with local institutional stakeholders and public bodies. In particular, the role of facilitator consists in bringing the different actors together, putting people together, establish contacts, gather opinions and ways of doing things, in order to implement concrete synergies.

System thinking

IS facilitators needs cross-sectorial and multi-stakeholder approaches. Due to the complexity of IS networks, it is necessary to subdivide the problems into small ones while being aware of the big picture. On this subject, the use of system thinking approaches aims at solving possible problems or discover possible "hidden" shared value, through the definition of common and realistic circular roadmaps, visions, interests and action plans at territorial level.

Legislation (& environmental economics & policy)

Facilitators should be familiar with EU, national and regional regulations, legislation and policy concerning waste management and circular economy to develop regulatory compliance. This is important in order to lead the project in the right direction.

Waste & recycling, Environmental skills

The IS facilitators should have a good knowledge of waste management, waste prevention, re-use and recycling issues to evaluate the project's impacts. This can help the facilitator to make bridges between the different sectors.

Soft skills

Soft skills are very important. In particular, the main soft skills are: team management, ability to question oneself, change management, active listening skills, thinking outside the box, will to learn, creativity, negotiation skills.

Entrepreneurship

The entrepreneurship skill includes important competences: ability to manage interpersonal relationships, creativity and innovation, goal setting, adaptability and flexibility (resilience), time management, willingness to take risks and to learn, leadership and teamwork.

Financial management skills

It is also very important to be well-informed about the main relevant co-financing instruments available at regional, national and European level. In addition, the facilitator should feel comfortable with the preparation and submission of different kinds of funding proposals.

MFA (Material Flow Analysis) & LCA (Life Cycle Assessment)

Although they require technical skills the facilitator must be able to read and understand the results of such analysis as well as he needs to be confident with data collection and management.

Marketing - Communication

Effective and empathetic communication is required to gain trust and convince companies and public authorities of the relevance of IS. In addition, the promotion of the project and the dissemination of the best practice processes represent important skills of facilitators.

IT skills

IT tools and skills are also important, in particular for helping the facilitator to be more efficient and organised in some tasks, such as data management and ecosystem mapping.

The role of external actors is fundamental for accelerating symbiosis, as they provide managerial, financial and regulatory support to companies. They help to facilitate communication and cooperation among parties, by also providing a knowledge conduit between industrial clusters. In addition, they support eco-industrial development by establishing collaborations between the industrial clusters and research institutes.

Synergistic relationships are further supported by partnership through the development of new business models. On this subject, the following components have been identified (Luciano, 2016):

- Increasing the biodiversity of the firms within the productive sectors as well as involvement of underrepresented companies.
- Providing companies technologically able to reuse residues in their production processes in sustainable way with the technical information for the potential use of available resources.
- Increasing the participation of local stakeholders and control authorities during operative meetings to ensure greater confidence in the symbiosis approach to companies as well as a greater awareness of the same stakeholders of the real potential of the approach.
- Encouragement of paths not financially attractive but that can have a strong positive impact on the environment.

One of the most important social characteristics for IS is the trust between the workforce of an industry and their bosses. In particular, the development of a mutual trust requires time and regular meetings. Moreover, it is associated with a decision-making approach and a certain degree of reciprocity (De Groen, 2018). The role of trust in the development of IS exchanges is based on the local support in promoting social relationships between initiators of IS exchanges (e.g. the managers of a company). On this subject, it is expected that IS enhances social equity within communities as it provides the need for professional and strong relationships between the involved actors. The implementation of IS in an existing industry can produce positive effects for the local community, such as an increase in well-being and job creation.

The revitalization of an industry through IS can positively affect its workforce, in terms of satisfaction increase, due to work under better conditions and to potentially learn new skills. Furthermore, the worker's commitment and trust can increase and, in turn, can enhance the revitalisation of the industry, resulting in more jobs creation, and in more increasing satisfaction, commitment, and trust of the workforce. In order to establish this positive loop, the appropriate education is needed, as, without education and the right implementation of the education, a knowledge or skills gaps, job and skills mismatching, or a lack of incentive from the workforce would hinder the industry revitalisation. In addition, the education design should involve the local community in the development of the IS network should include institutions important for the working activities of that community. The relation between the employer, employee, and the local community is very important for the successful of an IS network. In addition, it requires a certain degree of reciprocity and trust between employers established in a strong and professional way, resulting in the increase of the social equity within communities and, consequently, in sharing a sense of collaboration and responsible orientation among communities. IS initiatives can promote local economy and growth, create new business opportunities, help transfer knowledge and new skills, and contribute to the sense of community.

The most important social conditions related to IS, according to (Ashton, 2017), are as follows:

- Trust, openness and cooperation among firm(s) personnel;
- Strong social network ties or social capital;
- Knowledge creation and sharing;
- Embeddedness (cognitive and social).

As adopting IS requires knowledge in multiple aspects, such as technical and organisational expertise, and many people do not have awareness of IS concepts or sufficient understanding of IS terminologies, training for implementing IS can overcome lack of mechanisms to educate potential stakeholders (Vladimirova, 2018).

Concerning **training** offers theory and practice should be the main aspects to be covered as well as case studies including practical experimentations and visits. The trainer skills should be mainly focused on autonomous work, networking skills, combined with technical skills such as Eco-design, Life Cycle Thinking.

By going into detail, for developing IS, the following recommendations are proposed (INSIGHT):

- It is important to **introduce** the training with module on **basic knowledge and concepts**: IS core concepts, basic understandings, theoretical frameworks and methodologies.
- The most important skills are **interpersonal skills** - the ability to network, collaborate, think systemically, develop an entrepreneurship mindset and other soft skills. They also help overcome the social barriers.
- The trainees should be equipped with effective **communication** competences and **facilitation and collaboration tools**.
- The **legislation knowledge** can overcome **legal barriers**. In particular, the knowledge in waste management, waste prevention, re-use and recycling is very important, and it is a very complex matter, depending on EU, national and regional levels.

- Political support, financial incentives are considered the most important lever for IS implementation, while economic barriers are perceived as the third more important barrier. Consequently, the training should develop a module on **financial considerations, funding opportunities and business model skills**.

6.3 The workforce in Energy Efficiency

Energy efficiency practices implementation can potentially reduce building fuel cost, mitigate greenhouse gas emissions, improve energy independence, and enhance economic productivity. On the other hand, energy efficiency can be improved with (Sooriyaarachchi, 2015):

- educational and awareness programmes, influencing individual energy consumption patterns;
- implementation of policies and regulations to enforce the adaptation of energy efficiency measures;
- introduction of incentive programmes encouraging the energy efficiency measures implementation.

On this subject, Voluntary Agreements (VAs) contributes to deliver energy savings and emission reductions through the increase of energy efficiency in different sectors. In particular, the effectiveness of VAs strongly depends on the political will and engagement in investing resources and the efforts to design, implement and evaluate this policy tool (Rezessy, 2011). When it takes place through the cooperation between public authorities and the private sector, VAs can lead to advantages to public authorities in comparison to legislation, better flexibility, greater acceptance by industry, possibility for tailor-made solutions.

Due to the gap between the solutions available and the actual implementation in industrial companies, new approaches, developed in collaboration of academia and industry, can be applied in manufacturing companies and can facilitate the diffusion of management approaches for energy efficiency across industry (Bunse, Vodicka, Schönsleben, Brülhart, & Ernst, 2011).

The effects of the different policy measures added to the energy measures at sectoral level have been analysed (Ranieri, 2013). In particular, these measures are:

- incentives for employers to hire additional workers (i.e. lower taxes on labour);
- incentives for individuals to offer their labour (i.e. reduced welfare payments);
- greater investment in research and development (i.e. higher levels of R&D financing).

These measures can cause a decline in activity in conventional fossil-based energy sectors as well as in energy intensive sectors (e.g. cement, chemicals, iron and steel), resulting in higher prices of products supplied by them. At the same time, sectors that provide goods and services to manage energy more efficiently (creating jobs in construction, mechanical and electrical engineering and their supply chains) and non-fossil based energy sectors expand. The considered measures are designed in order to generate employment in labour-intensive industries, that can have advantages from the incentives provided.

As part of the Clean Energy for all Europeans package of measures, the European Union has issued the RED II Directive (Directive 2018/2001 EU) which aims to promote renewable sources. This Directive, recognizing the configurations of self-consumers of energy from renewable sources (art. 21) and renewable energy communities (art. 22), provides for the strengthening of awareness and the assumption of an active role of the consumer, who becomes a central figure in the transition energy (I Quaderni per la Transizione Energetica: Comunità Energetiche Rinnovabili e Gruppi di Autoconsumatori, 2022). In this context, a recent work aims to cover the process underlying the conception and implementation of a CER (Comunità Energetiche Rinnovabili = Renewable Energetic Communities) by providing an in-depth analysis of the main legal models that can be used for the establishment of such entities, taking into account their peculiarities and the objectives they intend to pursue. To this end, the general characteristics of the main models currently recognized by the legal system, with which it is possible to create a CER, were described (I Quaderni per la Transizione Energetica: Comunità Energetiche Rinnovabili e Gruppi di Autoconsumatori #2 - Principali modelli giuridici per la costituzione delle Comunità energetiche rinnovabili, 2023). These models were analyzed in their essential elements, highlighting the strengths and weaknesses of each, with the clarification however that the exact configuration of these can only depend on an accurate analysis of the specificities of the individual case.

Although some researchers think that Renewable Energy (RE) Technologies implementation can negatively affect the employment, the real impact depends on the applied methodology for assessing its impact. In particular, the transition from fossil fuels to RE will affect labour markets, leading to:

- the creation of new jobs;
- a shift from fossil fuel oriented sectors to renewable sector;
- the elimination of certain jobs without direct replacement;
- the redefinition of skill requirements for jobs.

In order to overcome the difficulties for planning investment and for delivering the requisite skills training, government and industry in response VET programmes have to:

- update or realign skills in the existing labour force, and those increasingly in demand (upskilling and reskilling);
- develop training capacity and equip the young, and disadvantaged people with relevant skills, for their integration into the workforce (skilling);
- develop processes to support the effective matching of skills supply and demand.

In order to implement workplace learning for green skills it is important to equip the workforce to support the transition to a low-carbon economy. This implies the acquisition of skills to manage managerial and technological changes and, consequently, technology, engineering and mathematics (STEM) related skills and the workforce skills require regular updating. In addition, these skills will be conditioned by the specific nature sectors and technologies, and their role in the low-carbon transition. Consequently, national responses need to be more flexible and dynamic at sector and/or local and regional levels.

Gaps in skills supply are possible when sector activities start quickly or change rapidly. This can negatively affect the training and education providers to react to these rapid changes in skill demands (Sooriyaarachchi, 2015). In particular, design the course and then obtain necessary approvals and funding require time as well as the courses preparation, including, for instance, the development of course materials in order to attract students and trainees. In addition, shortage in the availability of trainers and educators represents a further constraint, especially when the demand for sector skills emerge relatively suddenly.

In order to overcome this gap on future skill requirements and implementing relevant training and education programs, possible skill responses can be summarized as follows:

- Providing education and training courses for technical skills development through vocational training and education colleges and apprenticeships.
- Shaping university level courses by changing the existing content or adding new courses in order to meet sector skill demands.

- Continuing education and training on technological advancements and providing to non-technologists a basic understanding of technological problems, as well as of regulatory and legal implications.
- International linkages in renewable energy qualifications in order to standardize skills and qualifications requirements across countries globally and to allow international mobility.

Improving training and certification programs for the operation of energy systems and making these programs available is very important. In particular, the development of training programs focused on energy efficiency should provide a reasonable level of technical depth, hands-on field training, and easily accessible information about the content. In addition, certification programs on the energy efficiency of industrial energy systems can help to develop a more qualified and stronger national and international workforce (Guo, 2017).

A model learning-factory for energy efficiency (ETA-Factory) a holistic approach for an energy efficient factory has been examined (Abele, 2016). Its objective is to combine the real-life-experience of learning factories with the advantages of digitized learning. In particular, a training concept for transferring the multidisciplinary technical and methodical know-how about the proposed energy efficiency measures to industry and engineering students has been implemented.

In order to identify energy efficiency potentials in a production process, competences to transfer theoretical knowledge to practical situations are required. Consequently, an approach with repeated exercises and transfer to new situations can lead to achieve new skills. This can be do through the adaptation of the curriculum and the learning methods to the target audience and the topic.

The approach aims at integrating an intensive interaction with real technical equipment in a modern production environment. This is achieved by energetic measuring and by direct process optimization and simulation tools in order to evaluate energy efficiency measures and technologies, by combining the advantages of a 'classical' learning factory with the creation of an ambient learning experience by new media. This direct implementation can allow theoretically learned aspects of energy efficiency to be tangible and, consequently, it supports learners to consolidate knowledge and to develop knowledge.

In the last few years a customized educational solution called EUREM (European Energy Manager), involving the training of energy experts in energy efficiency, has been performed (Sucic, 2017). It represents an educational solution for training energy experts in the field of energy efficiency, covering almost all the energy relevant issues that can affect public and private companies. It also provides a solid basis for increasing the knowledge and skills of energy managers. Regular surveys and communications involving former training participants indicate that the EUREM training program has stimulated Slovenian energy managers to make significant energy savings in their companies. In particular, the strengths and weaknesses as well as the most important targets and challenges of the customized educational solution EUREM have been outlined.

Achieving EE in different sectors is crucial for contributing to a productive, sustainable economy. The integration of EE concepts into courses across a range of disciplines, not only engineering and science, aims at educating groups to work with cross-disciplinary teams. For this reason, it is crucial to develop appropriate teaching resources and certification and to introduce them across most disciplines (Pears, 2020). In this context, a recent project **RENSKILL** (RENSKILL, s.d.) ("Identification of the Skills and Competences Needed for the Professionals in the Renewable Energy Sector of the Future") aims at identifying the Skills and Competences

Needed for the Professionals in the Renewable Energy Sector of the Future. It can contributes to social impact by aligning policies of administrations, curricula of training agents and training plans of companies to promote renewable energies.

The challenge to the future development of EE is to stimulate the growth of the industrial sector to achieve set targets and to enable a transformation towards a low-carbon economy. For this reason, energy managers should be able to have a clear and efficient vision of a future energy development strategy, and it is crucial to provide the background to decision makers when they are dealing with energy-related issues. This can be achieved through the integration of energy efficiency into daily operational practice in a continuous process that requires additional skills and interdisciplinary knowledge related to energy management, renewable energy sources, energy auditing, building and facility management, energy trading, economics, financing, production planning and maintenance. Nevertheless, as energy technologies are changing very rapidly, the training-material should be updated and further developed. In this context, designing, managing and maintaining production models with reduced environmental impacts, by adopting enabling technologies, and operationalizing investments in new digital technologies, is crucial and requires a complex transformation of the skills of the workers. In particular, Artificial Intelligence and tools that rely on data-driven approaches can support companies in this transformation. In a recent work, the Energy Worker Profiler, a software designed to map the skills currently possessed by workers, was presented (Fareri, Apreda, Mulas, & Alonso, 2023). It aims at identifying the mismatch with those they should ideally possess to meet the renewed demands that digital innovation and environmental protection impose. Starting from the detection of key technologies and skills for the area of interest, this software can identify green and digital skills and professions that enable them. In particular, the assessment process aims to be data-driven, efficient and easy in order to replicate in other contexts and industrial sectors, by offering evidence-based approaches to improve the maturity and workforce skills towards digital and sustainable industries of the future.

In a study carried out in 2010 (Goldman, 2010) the need for additional education and training to meet the demands of a growing workforce to provide energy efficiency services has been highlighted. Several solutions have been provided, such as energy efficiency-related education programs as well as energy efficiency trainings for the building and construction trades. The study has also provided some recommendations, as follows:

- Provide energy efficiency education and support targeted at building and construction contracting and tradespeople;
- Coordinate and track training efforts within states; share best practices across states by identify and determine those programs/courses providing education and training for the energy efficiency services sector;
- Increase short-duration, applied trainings to augment on-the-job training and/or introduce new entrants to a field;
- Increase funding to “train the trainers”;
- Increase access to on-the-job training for mid- and senior-level engineers and managers;
- Prepare the next generation of Energy Efficiency Services Sector (EESS) professionals.

The core elements for designing specific VET programmes are, as follows:

- **Social dialogue** and collaboration between various government representatives and social partners, in order to identify training needs and design the process. Social dialogue allows the communication between industry representatives of the domain and government representatives responsible for ensuring skills needs. Cooperation within between education and training representatives of government and those responsible for implementing low-carbon policy can also allow that training responses consider the information on policy drivers of change. The dialogue may be local, regional or national.
- **Advice for the renewal of qualifications and accreditation systems.** Qualification ensures that training to emerging skill needs present appropriate content and standard. Not all initiatives related to skills for a low-carbon economy involve the formal adjustment of VET system content. Many of the relevant skills are delivered through short training and workplace learning from strong social partner engagement.
- **Procurement of training provision** to tailor training delivery at anticipated or identified needs. Procuring targeted training provision are preferable rather than depending exclusively on existing and established provision. Skills and training needs should combine a mixture of quantitative and qualitative methodologies. The procurement of training provision can develop innovative solutions to respond to particular challenges for employers and individual learners.
- **Monitoring and evaluation of program activity.** Monitoring and evaluation are essential for establishing confidence in skills needs analysis and value for money. Monitoring and evaluation processes help drive the renewal of qualifications and accreditation systems, highlighting effective training responses.

Due to the variation across Europe in approaches to VET in response to low-carbon economy developments in different domains, it has been highlighted the need to modernise VET systems in order to develop programs for delivering the skills needed. The **policy actions** should include the following recommendations:

1. Integrate low-carbon and skills development strategies. The identification of skills needs and design and implement relevant training responses to support a low-carbon transition are crucial as well as the promotion of integrated programs at sectoral, regional and municipal levels and to design VET responses aiming at tackling the skills challenges which risk inhibiting low-carbon policy implementation.
2. Develop joined-up policy responses to meet employment and low-carbon goals. Policymakers have a wide range of labour market, skills, economic and energy policies available to them to promote job creation.
3. Develop new and adapt existing systems of social dialogue between government and the social partners, to develop and design VET responses relevant to worker, employer and industry needs.
4. Promote institutional flexibility.
5. Develop and use labour market information to identify skills needs. In particular, social dialogue can support the development and relevant use of labour market information and training needs analysis.
6. Consider how procurement processes can achieve quality, cost-effective training. To achieve the full benefit of procurement processes, training needs and associated challenges have to be clearly articulated to tailor existing provision to specified needs and targeted groups.
7. Establish frameworks to monitor and evaluate new programs. Monitoring should be aligned with the strategic and operational program objectives and should also entail an assessment of cost.

8. Share and disseminate good practice. Developing a portal or repository of the good practice responses to VET across different sectors can help to showcase the findings of this and create a platform from which stakeholders can discuss practices and exchange experiences.

6.4 Training/Education/Policy Projects

ENACT (ENACT, 2014-2016) is an Erasmus+ project, which intends to harmonise and standardize the European and National frames related to the training and activities of the professional figures working for the energy efficiency of buildings. The objective of this project was to contribute to the definition and implementation of a common frame for the professional qualification and competences of energy auditors. Meaningful outcomes: 1) Improved management of buildings and increased their energy efficiency; 2) Increased innovation related to specific technologies and techniques for energy efficiency; 3) Increased training (quantitative and qualitative) on energy efficiency issues – new, well defined and structured courses to train the new figure of energy auditor according to the national/regional standards.

IFTS Circular Society (CircularSociety, EIT Raw Materials, 1 January 2020-31 December 2023) . Meeting Circular Economy challenges require well-trained people with technical skills of higher level. They will be able to think interdisciplinary, assess and model the consequences of anthropogenic interventions in the biosphere, and strive towards implementing measures to mitigate and reduce humanity's impact on the environment, while at the same time ensuring access to resources. The "HIGHER TECHNICIAN FOR REGENERATIVE CIRCULAR SOCIETY" training course has been established to address these challenges through higher technical education, which includes a strong work-based dimension coupled with an international training experience, appropriately integrated into the European qualification frameworks and systems.

The training course is a one-year higher technical education and training programme (IV EQF) aimed at obtaining a qualification of high technical level, organized thanks to an international partnership and the support of EIT Raw Material. The course will equip 20 European young people (preferably 18-24 year old), which are neither in employment nor education or training (NEET), with the necessary tools and skills in sustainable development, circular economy transition, management and implementation of intervention, impact evaluation methods, total quality management for environmental sustainability, as well as soft skills such as entrepreneurship and digital literacy. The overall training course is taught in English and is composed by 800 hours: 480 hours of theory and organized in Ferrara (Italy) and 320 hours of internship to be carried out in the European country of origin of participants.

The training course is developed under the IFTS Circular Society proposal, whom partnership consists of universities, VET and research and technology development organizations in Italy (Aster, Centoform), Finland (University of Oulu), Estonia (University of Tallinn) and Switzerland (myclimate Foundation). Moreover, the training programme is conceived and designed in collaboration with a European Faculty Board constituted by Academy, VET organizations, Industrial Associations and Clusters which will be also involved in providing training, teaching staff and internship.

Objectives: The project vision is to conceive, develop and certify a 1-year post secondary non-tertiary education pilot course that can be transferred at European level and be adopted by the

EIT Raw Materials Academy as a general framework for future VET courses. The target is young students preferably ranging from 18-24 years old, with a High school diploma as minimum requirement, from all EU countries. The two main objectives of the pilot course are the deployment and both its replication and transferability

Meaningful outcomes: Expected impact on trainees:

- they will get attractive and up-to-date training adapted to their needs and with a hands-on methodology based on cooperation at European level; benefitting of a more adaptive market oriented learning process;
- they will learn about Circular Societies sectors skills requirements and will be able to achieve deep knowledge of existing different jobs and careers offered by Circular Economy specialization nowadays in Europe;
- they will have the opportunity of learning in close contact with industries operating in the field, and practicing through in-company training;
- they will get an organized and certified training in Circular Economy issues which is not available at the moment outside the university curriculum;
- they will increase the opportunity of employability thanks to a business and academy connection, and VET figures;
- thanks to coherence of the training program with EU standard and templates of ECVET, they will be able to obtain the validation of learning units and achieved learning outcomes, up to recognition of credits in case of attendance of further training courses (i.e. Application of ECTS system by Universities).

RECYCLE ART (RECYCLEART, ERASMUS+, 2015-2016). The project consisted of: preparation, implementation, training, project management monitoring and controlling activities. These activities aimed to ensure: a proper project management, young people engagement in the project and future advances in the project. Key words: Learning Mobility of Individuals; New innovative curricula/educational methods/development of training courses Entrepreneurial learning - entrepreneurship education. Objectives: This project was addressed to 50 young aged 20-30 with the aim to incentive the waste reduction and high-quality separation by consumers as well as to create markets for recycled materials (standards, public procurement). Other objectives are the development of a circular economy and the creation of a social enterprises of recyclers as well as training youth people in the field of reuse and recycle art. Meaningful outcomes: The project impacts on young people were an enhanced interest in the field of energy waste, recycle and reuse; the creation of job opportunities and a networking in Europe; the development of an intercultural attitude and peacemaking abilities. The project partner organization took part in an innovative education activity and had the opportunity to share best practices, ideas and methodologies as well as to create a basis for further advances.

KATCH-e (KATCH-e, Erasmus+ K.A.2 – Knowledge Alliance for Higher education, 2017-2019). KATCH_e brings together 11 partners from four EU countries to address the challenge of reinforcing the skills and competences in the field of product-service development for the circular economy and sustainability in the construction and furniture sectors. The project aims to develop training materials, which focus on the competences necessary to generate product-service-systems based on the model of a Circular Economy. The application of life-time extending potentials such as cascade use, re-use or refurbishment is at the center of concern. The project aimed at: analysing the training needs, trends and policies regarding "design for CE"; setting up a stakeholder network to support the transfer of knowledge; developing and testing a problem- based and multidisciplinary course; creation of a MOOC and implementation of the above in academic and company contexts. Objectives: The development of the training materials, which focus on the competences necessary to generate product-service-systems based on the model of a Circular Economy. Meaningful outcomes: to support and promote the dissemination of circular design and sustainability among higher education centres and companies, demonstrating the practicability of the materials, their benefits and innovation potential.

SUPERMAT (SUPERMAT, Horizon 2020 The EU Framework Programme for Research and Innovation European H2020-EU.4.b. - Twinning of research institutions, 2016-2018). The project aimed to create a virtual centre to boost IMNR position in Bucharest-Ilfov region and Romania by increasing the knowledge and technology degree of innovation potential for sustainable advanced materials operating under extreme conditions as an area of key enabling technologies. A project WP was dedicated to education and entrepreneurship by: short training stages and 2 summer schools in ab-initio design and modelling of advanced materials and coatings with designed properties; training by research on new sintering and forming methods for obtaining high quality bulk nanostructured materials parts for critical environmental conditions; training by research on new coatings processing to produce surfaces with controlled properties for high temperatures and corrosion conditions; implement one common international PhD curricula in the field of materials for extreme environments; massive on-line Open Access Course (MOOC).

GT-VET (GT-VET, Lifelong Learning Programme - Leonardo da Vinci, 2011-2012). The project explored vocational education and training (VET) pathways meeting environment and health and safety skill needs, which are key for the global competitiveness and sustainability of all European industries.

As a model, the project developed an industry driven European sustainable training module in correspondence with national VET systems. A partnership of steel companies and research institutes, from each participating member state, identified and anticipated the impacts of environmental legislation on the everyday work of mechanical/industrial technicians and electrical technicians (for today and the future). Independent of the different VET systems of the member states, VET practices and learning outcomes were evaluated with respect to environmental skills, expertise and awareness. Based on these insights a European training module was developed to obtain identical European learning outcomes in the field of green skills and sustainable awareness complementing current technical VET programmes in this area.

Using the example of the steel industry and the VET of industrial, mechanical, electrical and electronic technicians, the modules and process of implementation became a blueprint for other technical VET professions and production industries (see project description of GREEN STAR) and for updating and implementation of training for new skills into the VET system, focused on meeting industry driven requirements for environmental sustainability in an immediate and responsive way. Objectives:

- The timely and responsive implementation of new mandatory skills within VET systems (national and industry related);
- To investigate the scope for the development of ongoing and responsive training pathways by focusing on skills for environmental sustainability;
- To develop a model of an industry driven and run European sustainable training module and to match the demands of industry with the VET system;
- To identify and to anticipate impacts of environmental legislation in everyday work of skilled workers, both for today and future;

- To develop a European training module to obtain identical European learning outcomes in the field of green skills and sustainable awareness within technical VET (focusing on preventing pollution and securing occupational health and safety);
- To adapt and to test the module within four steel companies and member states (United Kingdom, Poland, Italy and Germany);
- To use the example of the steel industry and the VET of industrial mechanics, electrical and electronic technicians for adaptation and transfer to other technical VET professions and production industries;
- To produce a blueprint for the implementation (process) of new skills for the industry sector and the appropriate VET systems.

GREEN STAR (GREENSTAR, Lifelong Learning Programme - Leonardo da Vinci, 2013-2015) is the transfer project of GT-VET project since it developed a Blueprint with all the relevant stakeholder as a co-creation process. Technical workers and apprentices in SMEs are provided with knowledge and skills to manage and implement smart and sustainable growth by reskilling & upskilling schemes and the integration of Green Skills in identified qualification levels. Doing this cooperation among VET, work systems and Triple Helix stakeholders was promoted co-creating a Sustainable Training Module for Automotive Cluster suppliers and adopt a cluster-driven approach to VET. Main tangible outcomes were Local Stakeholders Action Plans testing the adapted sustainable module. Additionally to the short term impact on Automotive suppliers cluster, workers and apprentices directly involved, the involvement and assessment of external stakeholders guaranteed further transfer opportunities to other clusters and VET sectors. With notable participation of TUDO GREEN STAR has developed the GT-VET Blueprint for large steel companies further as a blueprint for SME clusters along the value chain. Objectives: GREEN STAR aims to support the systemic change toward eco-innovation in the cluster of automotive suppliers, mainly SMES, by transferring the Leonardo DOI "GT-VET" Sustainable Training Module for the European Steel Industry (Large Enterprises) and the Blueprint for the implementation process of green skills for the industry in coherence with different national VET systems in Italy, Spain and Romania. Meaningful outcomes: A LITERATURE-BASED ANALYSIS: The Green STAR literature-based analysis, rather than a classic literature review, represent a proposal to provide a common framework and a starting point for reflection and discussion for stakeholders. About 270 papers and reports have been analysed by the keywords Automotive, Skills/ Competence, Sustainability/ Green, Cluster (Database Scholar and Scopus). 27 articles have been selected when containing at least two combined keywords.

ECOSISTER (ECOSISTER, National Recovery Fund (PNRR); 2022-2025) "Ecosystem for sustainable transition in Emilia-Romagna" is a cross-sector project. In order to maintain a leadership role in the international context and remain anchored to the vocations that characterize the Emilia-Romagna region (Italy), the ECOSISTER project intends to support the ecological transition of the regional economic and social system through a process that transversally involves all sectors, technologies and skills, combining digital transition and sustainability with the work and well-being of people and the defense of the environment in line with the objectives of the Pact for Labor and Climate, and integrating with regional, national and European programs. The partnership is composed by ART-ER and all the universities and research institutions based in the region, and which systemizes the skills of the High Technology Network, the services of the Incubators network, the relations with the territories of the Technopolis network. Companies and other actors of the regional ecosystem will be involved through "cascade calls". The project is organized in 6 spokes, each of them focusing on a specific innovation challenge area:

- Spoke 1 - Materials for sustainability and ecological transition
- Spoke 2 - Clean energy production, storage and saving
- Spoke 3 - Green manufacturing for a sustainable economy
- Spoke 4 - Smart mobility, housing and energy solutions for a carbon-neutral society
- Spoke 5 - Circular economy and blue economy
- Spoke 6 - Ecological transition based on HPC and Data Technology

CESME (CESME, INTERREG EUROPE; 1/04/2016-30/09/2020) project addresses SME inclusion in the circular economy, by interregional meetings identifying good practices aiming to examine how best regional and local authorities and business development agencies can improve relevant policy instruments and design support packages to assist SMEs to enter the circular economy. These initiatives will be implemented and tested for feedback and adaptation in order to be replicable tools across EU as well as monitored against their expected impact. Finally, this will lead to the improved effectiveness of the policy instruments addressed by the project partners. Objectives: through the creation of a return on investment analysis - Circular Economy Toolkit quantifying the economic and social benefits of circular value chains as well as a White Book guiding SMEs step by step into circular economy, the CESME partnership hopes to introduce new circular initiatives targeted SMEs.

MED SHERPA (SHERPA, INTERREG MED; 2023) project has been developed in order to answer problems identified in the MED area with regards to Energy Efficiency Buildings projects' implementation. SHERPA project's overall objective is to reinforce the capacities of public administrations at regional and sub-regional level within the territories covered by SHERPA so as to improve Energy Efficiency in their Public Buildings' stock and address difficulties related to energy efficiency in buildings projects in the Mediterranean area. Objectives: Roadmap to develop and implement EEB strategies; Regional EEB strategies supporting SEAPs implementation; Regional and local EEB Policy Agreements and governance structures; Shared information system; Public awareness strategies, including planning and implementation of specific trainings in EEB; Innovative combination and optimization of EEB financial models; Capitalisation plan; SHERPA Online Capitalisation Forum; Capitalisation set of toolkits; Joint Action Plan integrating all SHERPA EEB projects.

IMPULSE PLUS (PLUS, INTERREG EUROPE; 11/2020-05/2024) project will effectively transfer to new regions and cities the main outputs developed during the previous MED project IMPULSE. This includes the provision of support tools for the development of gradual renovation plans and financial planning for cost-optimal solutions for public building stocks. The Financial Scheme Evaluation tool, including the decision-making support tool PLUG-IN KPIs-processor for automated hierarchy of public buildings, will be revised and adapted under a transnational and cooperative way to help territories to meet the new targets set by the EU in the Green Deal and Renovation Wave Strategy, which aim to double annual energy renovation rates in the next ten years and report on the need to renovate buildings deeply on a massive scale. Objectives: IMPULSE introduced an integrated management support system for planning energy efficiency interventions in public buildings. The main challenge tackled has been the insufficient capacities of public administrations to set-up reliable and affordable energy efficiency plans for their public building stock, which at local level is reflected by missing or incomplete Sustainable Energy Action Plans (SEAPs). The main problem is the lack of available energy consumption data for the building stock and of easy-to-use decision-support systems to conclude the most affordable action plans with bankable and realistic solutions.

LEEWAY (LEEWAY, INTERREG EUROPE; 01/03/2023-31/05/2027) project aims to foster the adoption of energy policies for the creation of REC through the sharing and exchange of experiences between public authorities and regions. To get this purpose, the project foresees the participation of local and regional authorities, from different EU countries (ITA, BE, PL, D, HR) directly responsible for the elaboration and implementation of energy development policies, together with development agencies. Energy policies will take into account of suitable transition and social inclusivity, including competences. Objectives: through Study Tour, workshops and conferences at regional and interregional level, as well as mutual exchange of experiences, good practices and new ideas, each partner will be able to intervene on their energy policies related to the introduction of REC, also acting on policies concerning jobs and growth such as ROPs for the reference sector, improving the citizens well-being and contrasting the Energy Poverty.

CIRCOTRONIC (CIRCOTRONIC, INTERREG CENTRAL; 03/2023-02/2026) The environmental impact of electronics manufacturing is not just limited to waste creation but also raises concerns about air pollution, water and soil contamination in production processes. To overcome this, the CIRCOTRONIC project brings together scientists, entrepreneurs, and policy makers from nine manufacturing regions in a transnational network of regional circular labs. Together, they develop solutions for more circular value chains and design a policy framework for circular production, including competences upskilling and reskilling. Objectives: to create network of circular Labs, taking up solutions that were jointly developed and tested for improved circularity in EEE manufacturing SMEs covering the themes: 1. Materials 2. Design 3. Business Models.

6.5 Major conclusions on IS and EE effects on workforce

Policies to green the economy and policies to develop skills should be well connected. Labour market information that will anticipate and monitor skill needs for green jobs represents a crucial starting point for enabling governments and businesses to anticipate changes in the labour market, identify the impact on skill requirements, incorporate changes into the system by revising training programmes and introducing new ones, and monitor the impact of training on the labour market. The availability of a suitably trained workforce able to learn in turn encourages investment, technical innovation, economic diversification and job creation. In addition, leadership and management skills, enable policy-makers in governments, employers' associations and trade unions represent a priority.

In this context the creation of new jobs is expected to balance the unemployment resulting from the decline in more carbon-intensive industries. However, ensuring that disadvantaged groups will have the opportunity to access newly created green jobs will be a priority, as renewable energy also could cause more job losses indirectly.

In order to understand how the skill needs shift as economies go green the drivers of change should be identified. Changes in employment and in skills can be the result of four drivers of change (Cedefop, 2010):

1. physical change in the environment;
2. policies and regulation;
3. technology and innovation; and
4. markets for greener products and services, and consumer habits.

Changes in the physical environment require adaptation measures, in order to reduce the social costs of adjustment. Furthermore, physical change in the environment is the basis for policy decisions on environmental regulation. In turn, regulation can affect the development, availability and dissemination of technology. Regulation and the availability of technology can affect markets, both nationally and globally. On the other hand, consumer habits can affect companies business and encourage them to adopt new technologies in order to meet new consumer needs.

As pointed out in the case of the steel industry, but it is also applicable to other Energy Intensive Industries, a stronger collaboration between the industry, public bodies and education providers, is important to find and retain talents and to up-/reskill the workforce (COSME, 2020). In particular, the industry is interested in keeping close contacts with the relevant faculties and vocational institutions that represent important reservoirs of skilled labour. Partnerships between companies and educational institutions will increase in order to give to students the possibility to carry out traineeships or use companies as case studies.

Furthermore, the recommendations resulting by this study can be not only taken into account to the steel sector, but also to the other EIIs strongly involved in the application of the IS and EE concepts. By going into details, these recommendations are as follows:

- Monitor and anticipate steel industry skills needs
- Provide and promote training in transferable skills
- Expand and promote on-the-job forms of training
- Promote (reverse) mentorship as a way of knowledge transfer between older and younger workers.
- Encourage exchanges between public authorities, education providers and steel companies to promote digital and advanced technology skills, dual education and lifelong learning
- Promote social dialogue to ensure that as many workers as possible are included in skills development strategies
- Include underrepresented groups, such as women and migrants.

Future research activities in the context of social innovation will include different topics, such as regional, cultural and social context; outcomes and impacts of new practices to increase favourable social change; relationship to techno-logical and business innovation in processes of transformative change; a specific focus on the ambivalence of social innovations (Howaldt, Kaletka, & Schröder, 2021).

In the long-term a skill strategy, based on the assessment of the current state of the IS and EE implementations in EIIs and the determination of future skills requirements, should be elaborated. Based on implementing training programs for the workforce to obtain the required skills, this strategy should include fundamental sectors–academia cooperation to design appropriate education programmes. These can overcome the inconsistency between industry needs and human resources' actual capabilities and can help to attract and retain talents.

Going into more details, concerning technological and economic developments, the analysis of the workforce adjustment for IS and EE, results have shown that a multidisciplinary approach, mainly based on green and digital skills, is crucial as a new skilled workforce can manage the complexity of cross-sectorial cooperation in IS and EE implementation. In this context, digital skills are fundamental for implementing a pro-active skills strategy based on IS

and EE in different sectors. In addition, it is important building Science, Technology, Engineering, and Math (STEM) skills. Furthermore, the importance of 'soft skills', including collaboration, teaming, ethical judgement, and communication has been emphasized.
The main aspects of the Workforce in IS can be summarized. In particular, transversal skills/competences to all sectors can be, as follows:

- Openness for information sharing;
- Co-creation and cooperation to involve different stakeholders;
- Knowledge on the composition and development of products for developing innovative products based on secondary raw materials, residual waste or recycled materials;
- Managing a diversity of tasks;
- Applying innovative management tools to make the transition to circular economy;
- Increasing the biodiversity of the firms within the productive sectors and involvement of underrepresented companies;
- Providing companies technologically able to reuse residues in a sustainable way with the technical information for the potential use of available resources;
- Increasing the participation of local stakeholders and control authorities to ensure greater confidence in the symbiosis approach to companies;
- Encouraging paths not financially attractive but that can have a strong positive impact on the environment.

In addition, different skills, competences and knowledge are important for the of IS facilitator profile, as follows:

- Networking – Collaboration facilitation.
- System thinking
- Legislation (environmental economics & policy)
- Waste & recycling, Environmental skills
- Soft skills
- Entrepreneurship
- Financial management skills
- MFA (Material Flow Analysis) & LCA (Life Cycle Assessment)
- Marketing - Communication
- IT skills.

Concerning the workforce in EE, some main aspects can be summarized, as follows:

- Green skills to equip the workforce for supporting the transition to a low-carbon economy;
- Skills to manage managerial and technological changes: Science, Technology, Engineering, and Math (STEM) skills;
- Skills are conditioned by the specific nature sectors and technologies and their role in the low-carbon transition: national responses need to be more flexible and dynamic at sector and/or local and regional levels;
- Integration of energy efficiency into daily operational practice in a continuous process, requiring additional skills and interdisciplinary knowledge related to: energy management, renewable energy sources, energy auditing, building and facility management, energy trading, economics, financing, production planning and maintenance.

Clean technologies and energy-efficient applications will aim at achieving the European Union's climate targets in the next few decades. In this context, an adequate number of skilled workers and trained professionals will enable the green transformations, according to the European Green Deal.
The proposed strategies and highly transferrable good practices developed in the activities and projects across the involved sectors should be encouraged and promoted to foster skills

for the energy and green transition at local and regional levels. Successful training and education initiatives developed along with dedicated structures will boost energy and green skills and strategies to address future challenges.

7 Future Scenario on Industrial Symbiosis and Energy Efficiency in the involved Sectors

The context related to increased uptake of IS and EE due to raw material scarcity, decarbonisation of industrial process and stricter environmental policies has been considered. Based on achieved results, future trends and existing foresight analysis tools, mainly looking at the internal sectoral developed, are analysed and applied, in order to define a future scenario for process industry operations in five or ten years. This has involved industrial members of the consortium, belonging to the main sectors considered. In particular, specific objectives for each sector have been requested by providing a short questionnaire, to collect contributions on what it is doing within sectors on:
- Industrial Symbiosis: what are technologies, processes and where it is internally planned, on one hand, to do interventions on by-products valorization and treatment, and, on the other hand, interventions on process flexibility.
- Energy Efficiency: what are the objectives and how to do the sectoral foresight analysis, specifying where the energy savings are expected.

In addition, future scenario on effects of the uptake of IS and EE in terms of new skills requirement and training needs have been highlighted in the different sectors.
After 2 years, for the third version of the Deliverable 2.1, sector representatives have updated their contributions related to the short questionnaire, mainly looking at the internal sectoral developments, to analyse future trends in each involved sector, in light of the changes in the last 2 years (if there were any).

7.1 Steel Sector

In the steel sector, particularly focused on the EAF route, material and energy streams and services involved in symbiotic activities are, as follows:

Material streams OUT:

- Slags can be input materials that reduce usage of new resources in other sectors (e.g. basalt in road paving, limestone, marl in cement production, aggregates in building construction, etc.)
- EAF dust is a substitute of zinc ore in non-ferrous sector (zinc production, lead production)
- Iron bearing scale or sludges can be input materials for cement sector or chemical sector
- CO_2 from exhaust gas streams (from EAF or reheating furnaces) could be input material for chemical, agricultural, energy sectors

Material steams IN:

- Carbon bearing materials from biomass (agriculture, forestry, waste recovery) or from end-of-life plastics or tires can be substitutes of fossil carbon (coal, natural gas) for EAF process.
- Iron bearing materials as extension of scrap to lower quality fractions (waste recovery) valorizing their content for the use in EAF process.
- Water low quality streams from industrial district water treatment plants as substitute of more valuable sources.

Energy streams OUT

- Low temperature water (<100°C) from cooling water circuits can be an input for district heating.
- High temperature exhaust gases (500-1200°C from EAF or reheating furnaces) can be input streams for steam or electric energy production to be reintroduced in the supply grid local (steam) or wide (Electric Energy).
- High temperature irradiation (800-1200°C from steel and slag cooling beds).

Energy streams IN

- Hydrogen, H_2 locally produced from renewable sources for use in EAF and reheating furnace process as substitute of natural gas.

Industrial Symbiosis enabling technologies that will be developed and up taken in this sector include, as follows:

- Slag treatment plants for preparation of new input materials usable in road construction, cement production (slag dry granulation, slag sieving and grinding);
- Zinc production from EAF developed on EAF dust characteristics (e.g. EZINEX, IN-DUTEC, etc.);
- Hot cleaning of EAF exhaust gas, CO_2 capture from EAF exhaust gas stream, CO2 reuse (Methanol, ethanol production, etc.);
- Carbon bearing materials preparation for reuse in EAF (HTC process, Pyrolysis, gasification, torrefaction, etc.);
- Iron preparation (mixing, binding briquetting technologies);
- Scrap intelligent managing, tracking, monitoring, selection for quality upgrading for EAF use;
- Water treatment plants (inverse Osmosis, innovative UV, innovative filtration, etc.)
- Heat storage for buffering EAF discontinuous waste energy output.
- Energy conversion (ORC, TEG, etc.).
- Hydrogen production from renewables, transport, storage, mixing in grids, use in EAF or reheating furnaces.

Concerning developments of monitoring systems and new sensing devices, for improving characterization of process inputs/outputs to a better and targeted valorisation of by-products, processes in the steel sector need to become more and more predictable to reduce the spreading of properties of by-products or increase the recovery of waste heat. Consequently, it will increase online measuring and monitoring with dedicated sensors within a hardware and software architecture in order to supervise the whole process.

For scrap quality upgrading: technical improvements for the optical cameras monitoring system with the aim of a better scrap recognition and characterization during its movements within the scrapyard. These outcomes will be achievable through better camera sensors enable to the monitoring of all the light conditions, using polarized lenses to avoid scrap reflections, and increased frame per second acquired. In this scenario, the part belonging to the optical vision could be developed using Machine Vision and Computer Vision algorithms thus all the automatic scrap type recognition could be targeted to Machine Learning or Deep Learning. The use of a hyperspectral camera will be also useful as a tool for qualitative analyses concerning the scrap chemical composition. The laser scanner technology is also useful for real-time scrapyard monitoring and to analyze the specific scrap type in terms of volumetric dimension thus deriving its density.

For water: continuous online monitoring of the water flows involved in the circuits. The baseline is to use flowmeters (magnetic or using ultrasound), basin-level meters, and recording the digital output concerning the start and stop of the pumps in order to monitor the water movements within the basins and the plant. In addition to the stream monitoring, every edge could be analyzed using specific parameters (pH, conductivity, Total Suspended Solids, Turbidity, etc.). Operating in this way every water displacement is monitored in terms of volume and composition.

A tailored software architecture will be also fundamental to collecting all the digital signals coming from pumps and sensors. In this way, the water composition of each basin is achievable considering that what is arrived in that basin is known as what is already there. Besides the aspects of monitoring and supervision, the system could be auto-adjusted following specific goals, such as the specific composition of a basin, defining the maximum discharge of the water, or achieving a specific intake from the well.

Concerning digital technologies allowing smart and fast information exchange and even seamless connection of different steelmaking industrial production cycles, they include:

Artificial intelligence: Computer Vision or Machine Vision for effective image acquisition and concerning the use of hyperspectral cameras; Machine Learning or Deep Learning for the analyses of the images elaborated using Computer Vision techniques in order to develop the automatic scrap type recognition system.

Digital twins: used for plant status management and for detecting process anomalies or for predictive maintenance. It is founded on the collection of all the digital signals coming from a specific plant area and analyzed from a Machine Learning or more traditionally statistical point of view to detect in real-time what is outside the typical behavior.

DSS (Digital Support System): used for management of new material new energy sources or wide water treatment plants. This tool could enable the use of different Machine Learning models with the aim of simulating the changing of different parameters. Using Machine Learning algorithms DSS could suggest actions that have to be performed by the human operator or in a deeper integration it could act itself automatically following specific goals chosen by the human.

Concerning the future demand and market requirements with regard to environmental (greening of economy) and demographic challenges (growing aging population), the main issue for the future will be the carbon neutrality by 2050. Some consequences will appear as this topic will be tackled:

- Fossil carbon reduction and substitution with carbon neutral sources (biomass or CCU)
- CCU
- Hydrogen uses in processes

- Shortage of steel scrap, lowering of average scrap quality as a consequence of wider collection.

Aging of population can be tackled with an extension informatization of processes and digital supports.

Concerning the future effects of the uptake of IS on the personnel (in terms of new skills requirement and training needs), transforming a by-product or a waste in an input material or energy for another industrial process leads to standardization (quality, data science, results, analysis, quantities, etc.) as a necessity of interaction between symbiotic processes. This means an extension of factory production controls, quality measurements, logistic cares, etc. to the new product to be. This extension must be covered by the new skills and training of people.

On the other hand, concerning the effects of the uptake of EE on the personnel (in terms of new skills requirement and training needs), EE is already an important issue of actual processes, as consequence skills and trainings are already designed for optimization of this aspect. New efficiency can be gained by reducing energy waste flows: cooling water, energy of exhaust gases, energy of emissions from cooling beds of steel products. Recovery of energy from these flows means new processes with new technologies on which skills and training is needed.

7.2 Chemical Sector

The chemical industry in Europe is an important part of the European economy and a major and critical supplier to key industries, representing the basis of European's future competitiveness. Therefore, the chemical industry in Europe will face a number of challenges in the future, that will include increasing exports to regions outside Europe, the strengthening global competition, especially from incumbents of growing economies, rising energy and feedstock prices, pressure to increase resource efficiency, new regulations, and the need for innovation (CEFIC, 2022).

In order to make Europe climate neutral by 2050 the chemical industry represents the core of the European manufacturing to realize a climate-neutral society. In particular, the chemical sector is crucial for helping society to achieve the new European Green Deal objectives and in the next future it will provide circular solutions from wind turbines to electric vehicles.

The EU' ambitious targets call for the successful development and deployment of a portfolio of advanced process technologies and their combination in the chemical industry. Major technological priorities to reduce GHG emissions in the chemical sector include:

- The integration of climate neutral energy in particular through electrification, including:
    - indirect electrification for heat (low and high temperature e.g. e-cracker) and steam generation or upgrade;
    - direct electrification of chemical processes in particular through electrochemical processes;
    - utilisation of alternative energy forms.
- The utilisation of alternative carbon feedstock (contributing to carbon circularity):
    - waste including plastic waste through chemical recycling;
    - captured CO_2 (and CO from 'industrial waste gases');
    - biomass from sustainable sources.

- The production of hydrogen with a reduced carbon footprint for existing and expected higher future use of hydrogen as feedstock in the chemical industry, as well as future utilisation of hydrogen as energy carrier.

Such priorities would require new process technologies and their combination will be essential to reach climate neutrality objectives. Carbon capture and storage will also be part of the portfolio of options.

Advanced tools supporting decision making from design phase to production in particular **digitalisation** as well as **advanced materials** required for more sustainable chemical processes will also be key enabling priorities for the chemical sector.

Industrial symbiosis will contribute facilitating the implementation of some of the above-mentioned options through exchange of material or energy flows for heat integration for instance.

In the next few years, the chemical sector will create a significant "ripple effect" across many value chains relying on chemicals in order to remain competitive in the green and digital "twin" transition, through the Chemicals Strategy for Sustainability (CSS). In this context, the chemical industry will ensure the availability of competitively priced renewable and low-carbon energy. In addition, it will promote innovation and the deployment of breakthrough technologies, that will support the development of relevant infrastructure and facilitate access to public and private finance.

7.3 Refining Sector

In the Refining sector, material and energy streams and services involved in symbiotic activities are, as follows:

Waste residues: Refinery residues are mainly organic matrix residues, with a high residual calorific value (HCV). For this reason, they can be used as alternative fuels, directly or after partial treatment (drying, purification from the S, possible grinding), for example, the Eni Slurry Technology (EST treatment), which has a 5% purge at HCV>18 MJ / kg. Furthermore, *process water* treatment residues must also be considered, i.e. sludge deriving from the biological treatment of the water used in cooling (or for the purification of fumes, etc.). In addition, *exhausted process materials,* such as catalysts and exhausted filter cakes, must be considered. Other possible Waste to chemicals (W2C) materials to consider: Out of specification and by product, as Pet coke and out of specification bitumen.

Concerning IS enabling technologies that will be developed and uptaken in this sector, a whole series of W2C projects are currently underway, which through chemical, thermal or chemical-physical processes recover chemicals building blocks from residues. Projects are currently underway for the production of Hydrogen, methyl alcohol, ethyl alcohol and dimethyl ether. In addition, the oily sludge and bottom tank sludge are treated with a catalyzed hydrogenation process for the production of light gasoline (EST Project). So, the idea is to symbiotically supply materials for the chemical industry and solvents for the pharmaceutical industry. Off-specification materials and some residues can be validly used in the steel industry (instead of anthracite and as a foaming additive for slag, in the EAF), also partially replacing natural gas for heating above the steel bath. In general, given their high HCV, they can be (as is or partially easy treated) materials for the energy-intensive industry, such as metallurgical, cement factories, glass industry, etc.

Regarding developments of monitoring systems and new sensing devices for improving characterization of process inputs/outputs to a better and targeted valorisation of by-products, they include:

- Optical sensors, thermal pressure sensors, pH / ORP and conductivity sensors designed to tolerate extreme conditions;
- Digital Intelligent Sensor Management (ISM) technology, integrated in the probes, process control with Twin digital sensors.

Concerning digital technologies allowing smart and fast information exchange and even seamless connection of different industrial production cycles, they include: Digital Intelligent Sensor Management (ISM) technology, integrated in the probes, process control with Twin digital sensors, Optical separation Intelligent system for elimination of heavy metals and possible pollutants in off gas.

About the future demand and market requirements with regard to environmental (greening of economy) and demographic challenges (growing aging population), a recovery of refinery waste, possibly managed within the refinery itself, would make it easier to follow and trace the “path to the end of life” of these residues, which are potentially carcinogenic and teratogenic, if dispersed into the environment. Therefore, flexible technologies, easily handling, distributed and not centralized, cheap and easy to manage, would represent a great input for the internal production of materials useful for other industries. Drying / pyrolysis / gasification systems could provide materials for the chemical, pharmaceutical industry; physical briquetting or pelletizing systems could directly obtain materials useful for the energy-intensive industry.

Concerning the future effects of the uptake of IS on the personnel (in terms of new skills requirement and training needs), the best way to conduct the management of the treatment of refinery residues is to do this internally. Therefore, the personnel will have to be trained for this exercise, which requires engineering and advanced process control skills, such as Twin Digital system, Supervisors for monitoring and process control (flow rates, temperature, pressure, composition of off gases). It is also useful more specific skills capable of interact with the chemical / pharmaceutical / energy-intensive industries to collect their wishes and possibly correct the process inputs to get closer to the needs of the recipients of the products obtained from the treatment. Therefore, communication, administration, environmental engineering and basics of industrial chemistry skills. On the other hand, concerning the future effects of the uptake of EE on the personnel, many of the hypothesized processes (especially the thermal drying / pyrolysis / gasification ones) could be self-sustained, with a correct management of the process and with the internal recirculation of thermal waste. This requires skills in mechanical engineering, industrial chemistry (in relation to the knowledge of thermal processes) and competences on thermodynamic modeling, fluid dynamics and process control (latest generation automation).

7.4 Non-Ferrous Metals Sector

In the Non-Ferrous Metal sector, material and energy streams and services involved in symbiotic activities include: fabrication of base metals (Al, Cu, Pb, Zn, Ni), precious metals, specialty metals (Sn, Bi, Cr, Co, Ga, Ge, Zr, Ti, W, V, etc.) and rare earth elements (Ce, La, Nd, Pr, Sm, Eu, Y, etc.) from secondary raw materials and resources and design for circularity.

IS enabling technologies that will be developed and uptaken in this sector include:

- Additive Manufacturing of metal-based products from recycled materials.

- Bio-hydrometallurgical processes for recovery of precious and rare earth metals.
- Microwave processing of wastes, slags for reuse as raw materials in building materials.

Concerning developments of monitoring systems and new sensing devices for improving characterization of process inputs/outputs to a better and targeted valorisation of by-products, they include:

- Laser scanning systems for metals detection in wastes and scraps;
- X-ray fluorescence sensors for detection of metals from by-products;
- Thin films-based sensors for detection of harmful gases during processing of wastes and by-products.

In addition, digital technologies allowing smart and fast information exchange and even seamless connection of different industrial production cycles include:

- Cloud-based Smart Waste Management systems;
- Robotic systems for metals processing;
- Modelling, simulation and digital twinnings of processes.

Concerning future demand and market requirements with regard to environmental (greening of economy) and demographic challenges (growing aging population), they involve:

- Development and implementation of Information System for the Management of Non-ferrous Material Resources providing for the computerized management of wastes (all activities of collection, transport, treatment, recovery and disposal);
- Optimizing the collection and sorting infrastructure for metals scrap and products, to improve recycling rates;
- Improving product design, through requiring easier and more efficient disassembly, traceability, and recyclability of metals (e.g. for electronics waste).

Concerning effects of the uptake of IS on the personnel (in terms of new skills requirement and training needs), digital competencies will be required for personnel working along the whole value chain from detection of metals to final products; software for the design of materials and products must be included in specific engineering positions. In addition, it will be important to understand technology trends and evolution in the field, and the ability to learn and integrate new concepts and apply new methods / technologies. On the other hand, concerning effects of the uptake of EE on the personnel (in terms of new skills requirement and training needs) digital competencies will be required for personnel working along the whole value chain from detection of metals to final products. Other important requirements will be:

- Life cycle assessment knowledge to be implemented
- Best practice methods to be implemented in long life training courses for specialists and managers
- Understanding technology trends and evolution in the field, and the ability to learn and integrate new concepts and apply new methods / technologies.

7.4.1 Aluminium Sector

In the Aluminium industry material and energy streams and services involved for more easily engaging in symbiotic activities are bauxite residues, waste heat recovery, technologies at pre-competitive level e.g. CCU/CCS technologies.

IS enabling technologies that will be developed and uptaken in the Aluminium sector are, as follows:

- Substituting Natural gas by green Hydrogen
- Using solar energy/ renewable electricity for generating thermal energy which is stored, e.g. via molten salts
- Using renewable electricity in high pressure electric boiler (e.g. 30 MW)
- Use of electric and solar furnaces
- Technologies Increasing thermal stability of the electrolysis cells (including heat recovery)
- Use of green carbon sourcing for anodes used in smelters
- Advanced modelling & digital twins to eliminate anode reactions and PFC emissions
- Aluminium postconsumer scrap sorting per alloy family through digitalisation and robotics
- Melt purification technologies to remove contaminants included in post-consumer scrap

In addition, developments of monitoring systems and new sensing devices for improving characterization of process inputs/outputs to a better and targeted valorisation of by-products will concern:

- 3-D cameras, X-ray , LIBS technologies combined with AI for advanced post-consumer aluminium scrap sorting per alloy family.
- LIBS technology to measure the composition of molten aluminium

On the other hand, digital technologies allowing smart and fast information exchange and even seamless connection of different industrial production cycles will include:

- Developing more predictive and responsive manufacturing processes, e.g. by the use of digital twins, and integrating de-manufacturing/re-manufacturing concept in the supply chain should be a must.
- Artificial intelligence and digitalisation will be the turning point for the performance and productivity of the manufacturing industries.
- Predictive manufacturing, such as Digital twins, and the full exploitation of its potentials could be beneficial for the entire value chain.
- Promoting/developing low-carbon fully circular value chain, including material traceability and design for dismantling and recycling without any downcycling should be the key objective.
- A better integration of product design, manufacturing & de-manufacturing are essential, e.g. addressing the full value chain from design up to the end of life de-manufacturing for reuse or for recycling.
- More in general, increasing investments in R&D for low-carbon technologies and promoting scrap recovery and recycling

Concerning future demand and market requirements with regard to environmental (greening of economy) and demographic challenges (growing aging population), the European Aluminium Industry faces the challenge of decarbonization to meet ambitious climate goals. A study outlines a path to achieve net-zero emissions by 2050 while sustaining growth. With a projected 30% increase in demand by 2040, key levers for emissions reduction include swift decarbonization of electricity supply, inert anodes, low-carbon furnaces, and increased scrap recycling. However, achieving this comes with an estimated cost of around €33 billion. Proactive policy interventions are crucial, focusing on decarbonizing power generation, investing in low-carbon technologies, promoting scrap recovery, and supporting circular production. These measures are essential for the industry's competitiveness and long-term sustainability.

Effects of the uptake of IS on the personnel (in terms of new skills requirement and training needs) will include:

- Development of catalogue of best practices
- Best practice sharing among inter- and extra-industry stakeholders
- Cooperation with energy supply platforms for future-proof energy consumption solutions
- Plant-level programs for value creation with local communities
- Development of program for skills and competence

Finally, concerning effects of the uptake of Energy Efficiency on the personnel (in terms of new skills requirement and training needs) in the aluminum industry will require personnel to acquire new skills and undergo training in several areas:

- Technical Skills: Operation and maintenance of energy-efficient technologies.
- Process Optimization: Identifying and implementing energy-efficient practices.
- Data Analytics: Interpreting and analyzing data for process optimization.
- Environmental Awareness: Understanding the environmental impact and incorporating sustainable practices.
- Health and Safety: Training for safe operation of new equipment and materials.
- Regulatory Compliance: Staying informed about energy efficiency regulations.
- Collaboration: Developing cross-disciplinary collaboration skills.
- Continuous Learning: Embracing a culture of ongoing skill development.

7.5 Mineral Sector

In the Mineral sector material and energy streams and services involved in symbiotic activities are, as follows:
Material IN:

- Minerals unprocessed from the deposit.
- Water discharged form quarry or pumped from rivers
- Energy: From the grid; from own renewable sourcing in restored quarry areas.
- Chemicals: for some processing steps.

Material streams OUT:

- Minerals ready to be used in different applications to deliver different functionalities (e.g. steel making; ceramics; plastic; paper; glass; non-ferrous metal manufacturing; water purification; Hot Mix asphalt; Sludge treatment; etc.)
- Top soil: can be used for restoration activities within the quarry; Contribute to land management needs of the local community;
- Mining Waste can be used for restoration activities within the quarry or also as aggregates for the road construction and foundation in infrastructures.
- Waste water after cleaning can be pumped back in the river or can be used by other sectors for their needs.
- CO_2 from exhaust gas streams could be input material for chemical, paper making, energy sectors.

Energy streams IN

- National grid: Part of the energy needs for the processing of the minerals are supplied by the national/regional energy grid.
- Own renewables build-in capacity, in quarry restored areas, new renewable energy is produced thanks to installation of solar panels; windmills and also abiotic digestion capacity. Part is used in the industrial installations to reduce demand for the national grid energy.

Energy streams OUT

- Renewables, produced on-site part of this renewable energy is put back in the national/regional grid;
- Renewables, produced on-site part of this renewable energy is used in district heating and shared with the local community in the vicinity of the industrial operations;
- Co-generation: produced on-site. The challenge with this steam has been the energy price. In some occasions it was financially not rentable to use this source.

Concerning IS enabling technologies that will be developed and uptaken in the Mineral sector, Carbonation / Mineralization will create added value for multiple sectors especially to reduce and valorize waste flows. Some of the sectors that can benefit will be: Steel; Non-ferrous; pulp and paper; Water treatment; Construction material; Flue Gas Cleaning (Waste Incineration).

Project(s): Carbon Storage by Mineralisation (CSM);

In addition:

CO_2 material connectivity: Connecting CO_2 emissions with CO_2 users.

Multiple EU/national projects are delivering on this innovation area:

Projects: CO_2ncrEAT; Carbon for You (C4U);

CO2 to Hydrogen: Transform CO_2 to emissions to Hydrogen fuel:

Project(s): Columbus; Neutral Kero Lime (NKL)

Waste valorization: Construction sector;

Projects: Mineral Loop; CO_2ncrEAT;

Heat recovery: District heating when a surplus is produced on-site.

Concerning developments of monitoring systems and new sensing devices for improving characterization of process inputs/outputs to a better and targeted valorisation of by-products, Digitalization, will be the cornerstone to capture in real-time the improvements today and the hotspots that will need further action in the near future for all processing stages. The digitalization will be the tool to connect the missing dots for: 1. Production; 2. Waste management (e.g. mining waste; wastewater; air emissions); 3. Energy flows and 4. Finish products overall sustainability.

Predictable processing stages: Future innovative manufacturing and processing stages need to become more and more predictable to reduce the waste and boost the recovery rate for minerals. Consequently, it will increase online measuring and monitoring with dedicated sensors within a hardware and software architecture to have a good helicopter view of the entire processing life cycle stages.

For water: continuous online monitoring of the water flows involved in the different processing stages. A tailored software architecture will be also fundamental to collecting all the digital signals coming from pumps and sensors. In this way, the water composition of each basin is achievable considering that what is arrived in that basin is known as what is already there.

Digital technologies allowing smart and fast information exchange and even seamless connection of different industrial production cycles are, as follows:

Artificial intelligence: Computer Vision or Machine Vision for effective image acquisition and concerning the use of hyperspectral cameras.

Digital twins: used for plant status management and for detecting process anomalies or for predictive maintenance and minimize the shutdown time for maintenance.

DSS (Digital support System): used for management of new material new energy sources or wide water treatment plants.

Company specific technology developments. Difficult to get the information.

Concerning the future demand and market requirements with regard to environmental (greening of economy) and demographic challenges (growing aging population), the main challenge ahead is carbon neutrality by 2050. Some consequences will appear as this topic will be tackled:

- Access and reliable supply of Energy for the sector
- Competitive energy prices for the sector
- Access to low to carbon or neutral CO_2 intensity for the energy sources (e.g. Hydrogen, Biomass)
- CCU
- Proved technologies and viable supply of Hydrogen in the future as energy source
- CCS to store the surplus of CO_2 should be a viable solution.

Aging of population should be addressed in long-life learning and upskilling for the sector employees should be foreseen to anticipate and prepare for skill shortages and readiness for the challenges ahead. In addition, transforming a by-product or a waste in an input material or energy for another industrial process leads to standardization (quality, data science, results, analysis, quantities, et.) as a necessity of interaction between symbiotic processes. This means an extension of factory production controls, quality measurements, logistic cares, etc. to the new product to be. This extension must be covered by the new skills and training of people. The challenge is to have the same maturity as we have now for the EE positions also for the IS actual/future roles. The feedback we get by members of the Minerals sector is that they do not have a dedicated role of IS manager in the existing company organigram. They work on this in ad-hoc bases (EU projects to assess opportunities; threats, management of the confidential business information (CBI)) and do some testing on how to engage with local stakeholders (assess potential of urban symbiosis) and industries nearby (assess the potential of IS).

In one EU project, it was also found out that there is a need to train the authorities on the potential of the urban & IS, so the permitting that allows this to happen, moves quicker.

EE is a well-recognized role in the existing company organigrams and existing tasks. This allows to plan regular upskilling and training for these existing recognized positions. New efficiency can be gained by reducing energy waste flows: cooling water, energy of exhaust gases, energy of emissions from cooling beds of steel products. Recovery of energy from these flows means develop or connect existing processes with the help of new digital technologies on which skills and training is needed and should be anticipated.

The skyrocketing of the energy prices, during the last years, has indicated that energy efficiency is nothing more than timely to be addressed by companies further if there is a margin for further improvements at site level. Energy efficiency will also result in lower CO_2 emissions as well.

7.6 Water Sector

Concerning material and energy streams and services in the water sector for more easily engaging in symbiotic activities, depending on the sector, industrial wastewaters can embed a wide range of resources: water, energy, heating, nutrients, high added-value compounds.

Industrial wastewaters represent a rich source of various resources essential for symbiotic activities. These include water, energy, heating, nutrients, and high-value compounds, each offering unique opportunities for resource recovery and reuse. Water can be treated and reused for various purposes such as irrigation, cooling, or process water, reducing the over-abstraction of freshwater resources. Energy and heating present in wastewaters can be harvested through technologies like anaerobic digestion or heat recovery systems, contributing to energy efficiency and cost savings. Furthermore, nutrients and high-value compounds extracted from industrial wastewaters can be utilized in agriculture, pharmaceuticals, or other industries, fostering circularity, and reducing dependency on first raw resources. Services also play a crucial role in enabling symbiotic activities by providing expertise in wastewater treatment, resource recovery, and process optimization.

Concerning IS enabling technologies that will be developed and uptaken in the water sector, IS is enabling the demonstration of new technologies for water reuse, related to Technology, Software, Hardware, Business intelligence, Market analysis. Some examples of technologies currently under demonstration are: membranes for advanced Reverse Osmosis and membrane Distillation for near ZLD systems; zeolite adsorption for ammonia removal; Extraction of added-value compounds from wastewaters by filtration, adsorption and supercritical fluid; AnMBR with fit-for-purpose post-treatment; IEX for ammonia recovery.

In addition, developments of monitoring systems and new sensing devices for improving characterization of process inputs/outputs to a better and targeted valorisation of by-products will include: Real-time data driven monitoring and process control for salinity management; Online monitoring system for control of pre-treatment steps to reduce membrane fouling in AnMBR; Data-driven cloud-based control system for wastewater Treatment Plant operation.

Concerning digital technologies allowing smart and fast information exchange and even seamless connection of different industrial production cycles, they include: Water Smart Industrial Symbiosis; Digital Marketplace; Model and matchmaking algorithms generating symbiotic models; HMS simulation and stress testing platform; Interactive Gamified Visualization Tool; Data-driven matchmaking platform for water reuse to manage demand and supply; Digital twinning (Digital Twins integrate artificial intelligence (e.g., machine learning) and domain models with real-time data to create living digital copies of the physical infrastructure and thus change with their physical counterparts. The result is an integrated digital knowledge management system with which up-to-date system information is shared unambiguously and traceable with supervisors, water managers and citizens (on-line), and with which the consequences of potential measures can be studied by means of scenario planning).

Concerning the future demand and market requirements with regard to environmental (greening of economy) and demographic challenges (growing aging population), they necessitate a comprehensive approach to water management and resource utilization. To address these challenges, our focus is on developing exploitation and valorisation schemes tailored to Water-Smart Industrial Symbiosis (WSIS), creating innovative business models, establishing benchmarks for environmental and economic performance evaluation, exploring new governance approaches, reducing barriers for resource recovery and reuse, fostering collaboration between stakeholders in WSIS value chains, and leveraging digitalization to enhance efficiency and decision-making processes.

Concerning effects of the uptake of both IS and EE on the personnel (in terms of new skills requirement and training needs), they will be: needs for new skills; digital skills; vocational training; skills update; re-skilling.

7.7 Cement Sector

Concerning material and energy streams and services in the cement sector for more easily engaging in symbiotic activities, at this moment, the cement industry recovers energy from a variety of waste streams for 50% of its energy needs. There is no technical impediment to take that up to much higher levels, even 95% (some plants operate at that level). The restrictions are regulatory in nature: access to waste (due to lack of landfill bans); permitting; taxation etc. In addition, the cement industry also recycles waste materials. This recycling/recovery while producing clinker and cement is referred to as co-processing.

IS enabling technologies that will be developed and uptaken in the cement sector will be used as input into the cement manufacturing process (co-processing using 100% of end-of-life composite materials).

In addition, developments of monitoring systems and new sensing devices for improving characterization of process inputs/outputs to a better and targeted valorisation of by-products concern digitalization of the manufacturing process which allows optimization of the energy mix in the kiln.

Future demand and market requirements with regard to environmental (greening of economy) and demographic challenges (growing aging population) will include pressure from our downstream uses (contractors; construction companies) to deliver low carbon cement and concrete. Demand for concrete is likely to go up (infrastructure; sustainable housing; urbanization) but there will also be design efficiencies that result in use of less concrete per m^3.

Concerning effects of the uptake of IS on the personnel (in terms of new skills requirement and training needs), workers will need to be trained in handling of more and different waste streams as an input to the manufacturing process.

On the other hand, concerning effects of the uptake of Energy Efficiency on the personnel (in terms of new skills requirement and training needs), the cement industry is already operating at a high level of energy efficiency. The main focus is on CO_2 reduction. In particular, Carbon Capture and Storage will play an important part in the roadmap to 2050.

7.8 Ceramics Sector

The most ambitious goal of the Ceramics sector is linked to energy transition challenges introduced by the Green Deal. Strong commitments will be done from all sectors of the ceramic industry to meeting the goal of climate neutrality. In particular, it aims at becoming more sustainable by preserving raw materials and consequently limiting emissions associated with extraction. Concerning IS this sector has been working on this topic for decades and the main challenge is linked to the regulatory framework of raw materials. As most technical ceramics are inert and non-toxic, they are largely non-polluting and can be effectively reused and recycled. On the other hand, the energy-saving potential, durability, and reusable qualities of ceramic materials, with a renewed focus on EE and CE, will make the European ceramic industry to be central to reducing energy use and residues and waste (Cerame-Unie, Ceramic Roadmap to 2050, 2021). In particular, stating that secondary raw materials are a challenge because they see the constraints that waste could have and what hazards they could entail when being used. In addition, they also have legal constraints (e.g., in Portugal) as some are considered waste and not raw materials. In this regard, it is important to look into life cycle assessments and to not transport pollution from one sector to another or from one material to another.

IS is not an easy endeavour, as in terms of legislation there are also challenges in Spain - tight environmental regulations that hamper the use of waste. Moreover, is difficult for a small company to manage all the variables considered in IS. For instance, sometimes waste is more expensive than the primary raw material, so the investment is not justified for clay, and waste only substitutes a part of the raw material. In addition, it is hard to share information and best practices between companies because giving information about what type of waste is used and how, is sensitive to the competitiveness of companies. The ceramic industry as an SME sector, faces specific challenges to consider for IS and EE aspects. However, it is more challenging for SMEs to allocate resources to tackle IS, due to their smaller structure.

In order to reach the new targets new technologies will be required, although natural gas will not be replaceable in the immediate future. Consequently, targets will be to focus on green fuels that can replace natural gas, such as biogas/biomethane or hydrogen. For instance, by applying heat recovery from flue gases to preheat combustion air, significant reductions of the environmental impact embodied in their products can be achieved. In addition, despite the higher investment costs, the electricity self-production through photovoltaics strongly contributes to reduce environmental impacts and to higher economic savings (Monteiro, Cruz, & Moura, 2022).

As research and innovation in the ceramic industry has transformed the manufacturing process and the efficiency of raw materials, through innovative technologies and product developments, the substitution of primary raw materials with recycled materials, the direct internal reuse or recycling of materials and the substitution of conventional fuels will increase. However, to achieve this goal strong institutional supports to facilitate the research, development and application of new technologies will be required. Through the support of research and innovation in the ceramic industry on innovative technologies and product developments the substitution of primary raw materials with recycled materials, the direct internal reuse or recycling of materials and the substitution of conventional fuels will be achieved. In addition, digital technologies will play a crucial role in the product design. On the other hand, the application of digital printing in the glazing process will be a great potential.

For shifting to a climate-neutral, resilient economy skill sets and qualifications for future job profiles should be provided, by identifying skills shortages and ensuring adequate supply of the right skills for the green and digital transitions. Qualified people are needed to manage these difficult situations, how to find and prepare these resources, and how to be aligned with the legislation, by also including life cycle assessments in the pilot training course for awareness, as well as concepts of recycled material and secondary raw materials. In this context, big companies can create their own training programme whether smaller ones need more support to build their skills. On this subject, the European ceramic industry is committed to supporting the upskilling and reskilling of its workforce with continuous, specialised and lifelong training supported by collaborations with academia, educational providers and communities. In addition, the European ceramic industry is deeply rooted in local economies, and committed to create local jobs as an industry we aim to continue being a driver for local economies, innovation and employment.

7.9 Waste treatment Sector

Within the involved sectors the Waste treatment sector was considered, due to its significant role in some aspects of both IS and EE implementations.

Concerning material and energy streams and services in this sector for more easily engaging in symbiotic activities, residues which, according to European regulations (Directive 1999/31 / EC relating to landfills of waste), and implemented by the nations of the European Community, cannot be landfilled because they have an NCV> 13 Mj / kg. These are organic matrix residues, deriving from civil waste treatment, treated to make them stable (stabilized organic fraction) or purified to transform them into fuels (solid waste fuels: Refuse Derived Fuels (RDFs), are usually mixtures of dried wood, paper, plastic, and therefore, in general, all the residues with an organic matrix that could be used as raw materials in cement factories, calcific factories, glass industry, steel mills, both as reducing agents and as fuels.

Concerning IS enabling technologies that will be developed and uptaken in your sector, they will include RDF, residual biomass, other organic matrix wastes or industrial residues (e.g. by refinery) drying, purification and grinding systems, to make it suitable for also being injected with pneumatic systems, instead of being inserted with the charge (in the basket)

Concerning developments of monitoring systems and new sensing devices for improving characterization of process inputs/outputs to a better and targeted valorisation of by-products, they will include, in general, development of sensors and automation for:

- Magnetic and no-ferrous magnetic separation;
- Shredding to standard size;
- Rotary screen to remove the pieces of the standard size;
- Optical separation system: the separation occurs through the infrared optical beam that permits to recognize various polymers removing the material not suitable for the SFR.
- Use of AI and new sensor based on AI control (real-time monitoring, reference software, digital twin simulators and controllers collecting data of process robustness, production speed, yield and right first-time capability, process implementation time to strengthen the green deal and circular manufacturing processes and reducing waste of natural resource).

Concerning digital technologies allowing smart and fast information exchange and even seamless connection of different industrial production cycles, they will include the development of automation for:

- Magnetic and no-ferrous magnetic separation;
- Shredding to standard size;
- Rotary screen to remove the pieces of the standard size;
- Optical separation system
- Elimination of heavy metals, possible pollutants in off gas
- Computational methodologies to assist the design of the bioprocesses, resulting in a proof of concept that can be expanded to other feedstock and bioprocessing approaches (see VAIORISH project)

Concerning the future demand and market requirements with regard to environmental (greening of economy) and demographic challenges (growing aging population), the idea is to enhance even what is not currently recycled, by expanding the field of application of RDF (for example by grinding it and making it injectable to burners or injection lances in tubing or EAF). In general, a placement is sought at the EII, as an auxiliary fuel, once purified and eliminating the presence of heavy metals, potential pollutants in the off gases of the processes in which they could be used. All this by taking them away from the landfill. The pushed automation of the process, the use of advanced selection and control sensors would make the preparation process of this material less wearing and therefore more suitable even for more mature personnel.

In addition, concerning effects of the uptake of IS on the personnel (in terms of new skills requirement and training needs), the skills of the quality RDF production process will shift from manual to automated separation operations and will therefore have to manage intelligent sensor and control systems. The automation will be that belonging to the latest generation of artificial intelligence, (ex: Digital Twin (DT)) able to predict the evolution of the purification process along the RDF production line, until reaching the predetermined quality and suitable for the identified process. The knowledge of the control tools including AI allows to predict the values of the critical KPIs of the product, continuously updated with the actual values of the critical parameters of influence, measured in line, working at the same pace of the production line.

On the other hand, concerning effects of the uptake of EE on the personnel (in terms of new skills requirement and training needs), undoubtedly, refresher courses will have to be carried out in relation to the automation and control of the RDF production process, even if these are simple systems to manage. However, it should be considered, on the other hand, that there will be a great deal of simplification of operations and remote control will reduce the global impact that is currently very important (unpleasant odors, presence of toxic effluents, etc.) in manual waste management operations. The competence relating to the legislation on the “end of waste” path should not be overlooked, in recent years in continuous evolution, simplification and standardization at European level.

7.10 Conclusions on cross-sectoral Future Scenario

Concerning the IS implementation different sectors (e.g. Minerals sector) underline that it is not an easy endeavour, due to environmental regulations that hamper the use of waste. In particular, it is often difficult for small companies to manage all the variables considered in IS practices. On the other hand, it is hard to share information and best practices between companies due to sensitivity and confidentiality issues.

Concerning **developments of monitoring systems and new sensing devices for improving characterization of process inputs/outputs to a better and targeted valorisation of by-products**, it is important to make manufacturing and processing stages more and more predictable in order to reduce the spreading of properties of by-products or increase their recovery as well as to create added value for multiple sectors especially to reduce and valorize waste flows. For this reason, it is fundamental to increase online measuring and monitoring with dedicated sensors within a hardware and software architecture in order to supervise the whole process. In addition, real-time data driven monitoring and process control and online monitoring system for control of pre-treatment steps and data-driven cloud-based control system are fundamental for the different sectors.

Concerning **digital technologies** allowing smart and fast information exchange and even seamless connection of different industrial production cycles, for most of the involved sectors the following digital technologies will be important: AI, Digital twins, Digital Support System, Cloud-based Smart Waste Management systems, Robotic systems and Model and matchmaking algorithms generating ideas for synergies as well as modelling and simulation of processes. In addition, it is important to use digital technologies allowing smart and fast information exchange and even seamless connection of different industrial production cycles. These will include: Digital Intelligent Sensor Management (ISM) technology, integrated in the probes, process control with Twin digital sensors, Optical separation Intelligent system for elimination of heavy metals and possible pollutants in off gas. Furthermore, digitalization of the manufacturing process will allow optimizing of the energy mix, low-carbon technologies and promoting scrap recovery and recycling. In addition, an integrated digital knowledge management system with which up-to-date system information can be shared and traceable with supervisors, and can allow studying the consequences of potential measures by means of scenario planning.

Concerning the **future demand and market requirements** with regard to environmental (greening of economy) and demographic challenges (growing aging population), the main issue for the future will be the carbon neutrality by 2050 while sustaining growth. The idea is to enhance even what is not currently recycled, by expanding the field of application. On this subject, flexible technologies, easily handling, distributed and not centralized, cheap and easy to manage, would represent a great input for the internal production of materials useful for other industries. On the other hand, it is fundamental improving product design, through requiring easier and more efficient disassembly, traceability, and recyclability of by-products. In addition, the following fundamental aspects are underlined in different involved sectors: development of new exploitation and valorisation schemes based on business models and services tailored; new governance approaches; reduce barriers for recovery, reuse and commercial exploitation of valuable resources in IS; novel models of collaboration between stakeholders and leveraging digitalization to enhance efficiency and decision-making processes. Proactive policy interventions are crucial, focusing on decarbonizing power generation, investing in low-carbon technologies, promoting scrap recovery, and supporting circular production. These measures are essential for the industry's competitiveness and long-term sustainability.

Concerning the **future effects of the uptake of IS on the personnel** (in terms of new skills requirement and training needs), transforming a by-product or a waste in an input material or energy for another industrial process will lead to standardization as a necessity of interaction between symbiotic processes. Qualified people are needed to manage these difficult situations, how to find and prepare these resources, and how to be aligned with the legislation, including also life cycle assessments in the pilot training course for awareness, as well as concepts of recycled material and secondary raw materials. This means an extension of production controls, quality measurements, logistic cares to the new product to be. This extension must be covered by the new skills and training of people. For instance, workers will need to be trained in handling of more and different waste streams as an input to the manufacturing process. In addition, personnel will have to be trained for this exercise, which requires engineering and advanced process control skills. In particular digital competencies will be required for personnel working along the whole value chain. But also, due to needs for new skills, not only digital skills, but also vocational training, skills update, re-skilling will be implemented. In this context, big companies can create their own training programme whether smaller ones need more support to build their skills.

Finally, concerning the **effects of the uptake of EE on the personnel** (in terms of new skills requirement and training needs), EE is already an important issue of actual processes, as consequence skills and trainings are already designed for the optimization of this aspect. Recovery of energy from these flows means new processes with new technologies on which skills and training is needed and should be anticipated. Consequently, it will be important to understand technology trends and evolution in the field, and the ability to learn and integrate new concepts and apply new methods / technologies. In particular, personnel is required to obtain new skills and undergo training in several areas: Technical Skills, Process Optimization, Data Analytics, Environmental Awareness, Regulatory Compliance.

8 Survey Analysis

A survey has been carried out to determine the current state of Industrial Symbiosis and Energy Efficiency in the European Process Industry, considering the ongoing and past experiences, the expectations and foreseen efforts related to the possible adoption of the Industrial Symbiosis and Energy Efficiency solutions as well as the resulting impact on the workforce. To this aim, a questionnaire (See Annex) addressed to employees working in companies of the European process sector was launched in July 2020, and was expected to be available online by the end of 2020 at the following link:

https://umfragen.tu-dortmund.de/index.php/968675?lang=en

For the Second Version of the Deliverable, the questionnaire was reopened in April 2022. Compared to the previous version the only difference was the last question, in order to identify people that did not fill out the survey in 2020. It was available at the following link:

https://umfragen.tu-dortmund.de/index.php/325173?newtest=Y&lang=en

8.1 Structure of the survey

The complete text of the Questionnaire is reported in Annex I. Not all the questions were mandatory. The mandatory question are highlighted with an "*" in Annex I. Moreover, some questions were shown to the compiler upon conditions on previous question. This option was selected in order to avoid useless answers. For instance, if the compiler answered "*Not Yet*" to the question "*Does your company apply principles of the Industrial Symbiosis?*", He/She is not required to answer to the question "*What is the current level of Industrial Symbiosis in your Company?*", as the answer would have no sense. Instead, He/She is asked to answer to other questions, which aim at assessing if at least there is awareness in the company concerning the potentials of Industrial Symbiosis. For the sake of completeness, in Annex I the eventual conditions under which the question is shown are specified under the text of the question itself.

The flow diagram of the questionnaire is depicted in Figures 8.1-3. The survey is organized into three main sections:

- **Section I** covers the ongoing and foreseen implementation of Industrial Symbiosis and Energy Efficiency (see Figure 8.1) as well as the expected benefits. This section is split into two similar subsection, each one dedicated to one of the covered topics, as companies might also being implementing or foresee to implement solutions and practices dealing with one only of the two considered topics.
- **Section II** is dedicated to the technical aspects and covers the envisaged resource synergies, the adopted tools, the main actors and areas, which are involved in the ongoing or foreseen implementation of practices for Industrial Symbiosis and Energy Efficiency (see Figure 8.2). Similar but separate questions target Industrial Symbiosis and Energy Efficiency, as companies might also being implementing or foresee to implement practices covering only one of these aspects. The questions are accessed by the compilers, Who have answered positively to the initial questions of Section I concerning the involvement of their companies into practices related to Industrial Symbiosis and Energy Efficiency.
- **Section III** covers the foreseen impact of Industrial Symbiosis and Energy Efficiency on workforce and contains both generic questions and questions dealing with only one of the two concerned topics (see Figure 8.3).

A fourth section is also present, which is devoted to the collection of general information concerning the participants to the survey. It is not mandatory to fill all the fields: only the sector and the dimension of the company must compulsory be provided by the participants in order to submit the questionnaire. In particular, no personal information is required to the participant and even the name of the company is provided only on a voluntary basis.

In the following paragraphs the analysis of the results for each area based on the collected answers is reported.

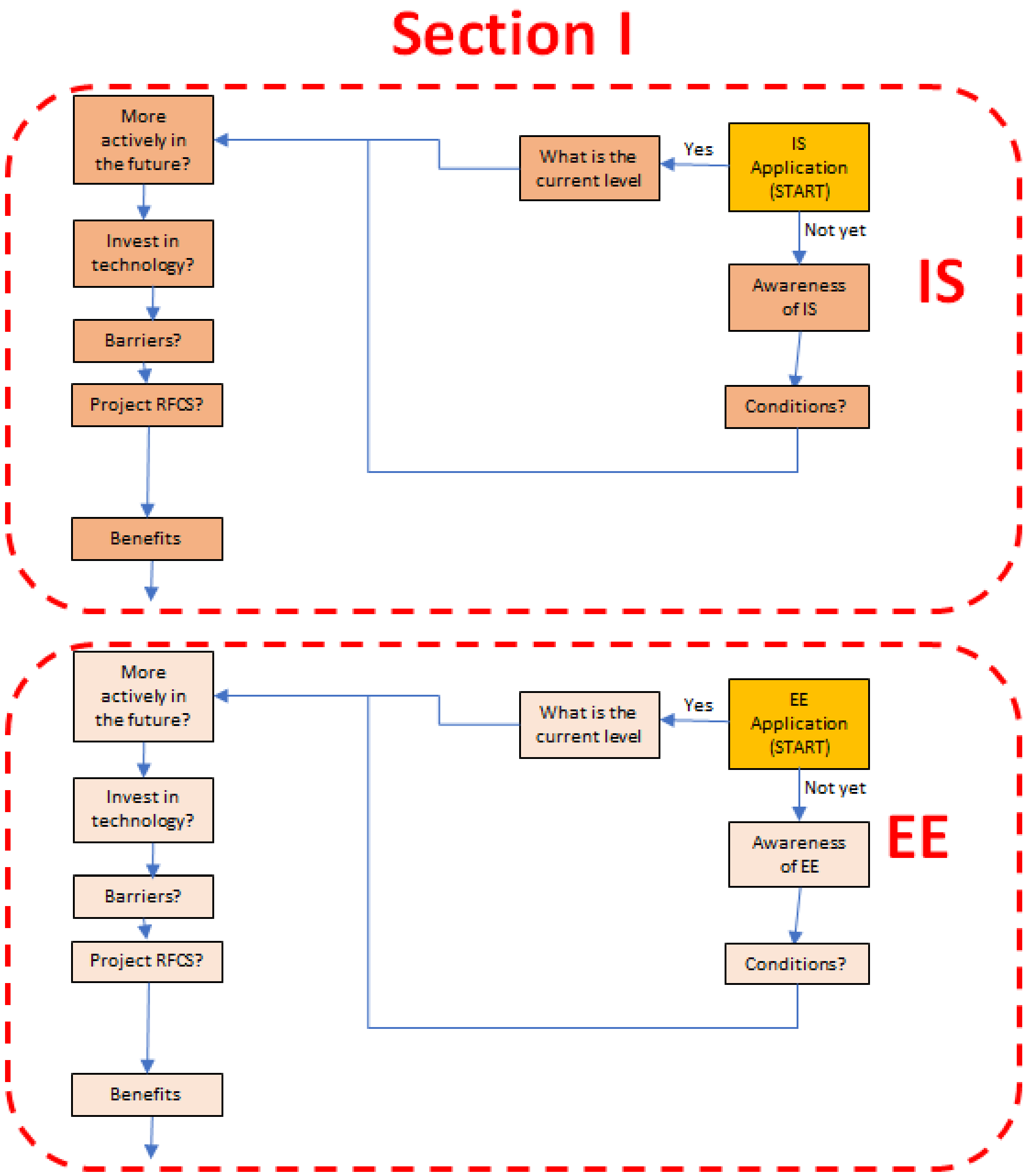

Figure 8.1: flow diagram of Section I of the online Questionnaire

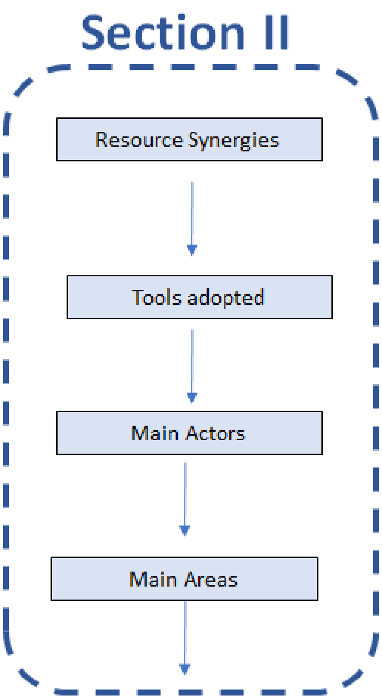

Figure 8.2: flow diagram of Section II of the online Questionnaire

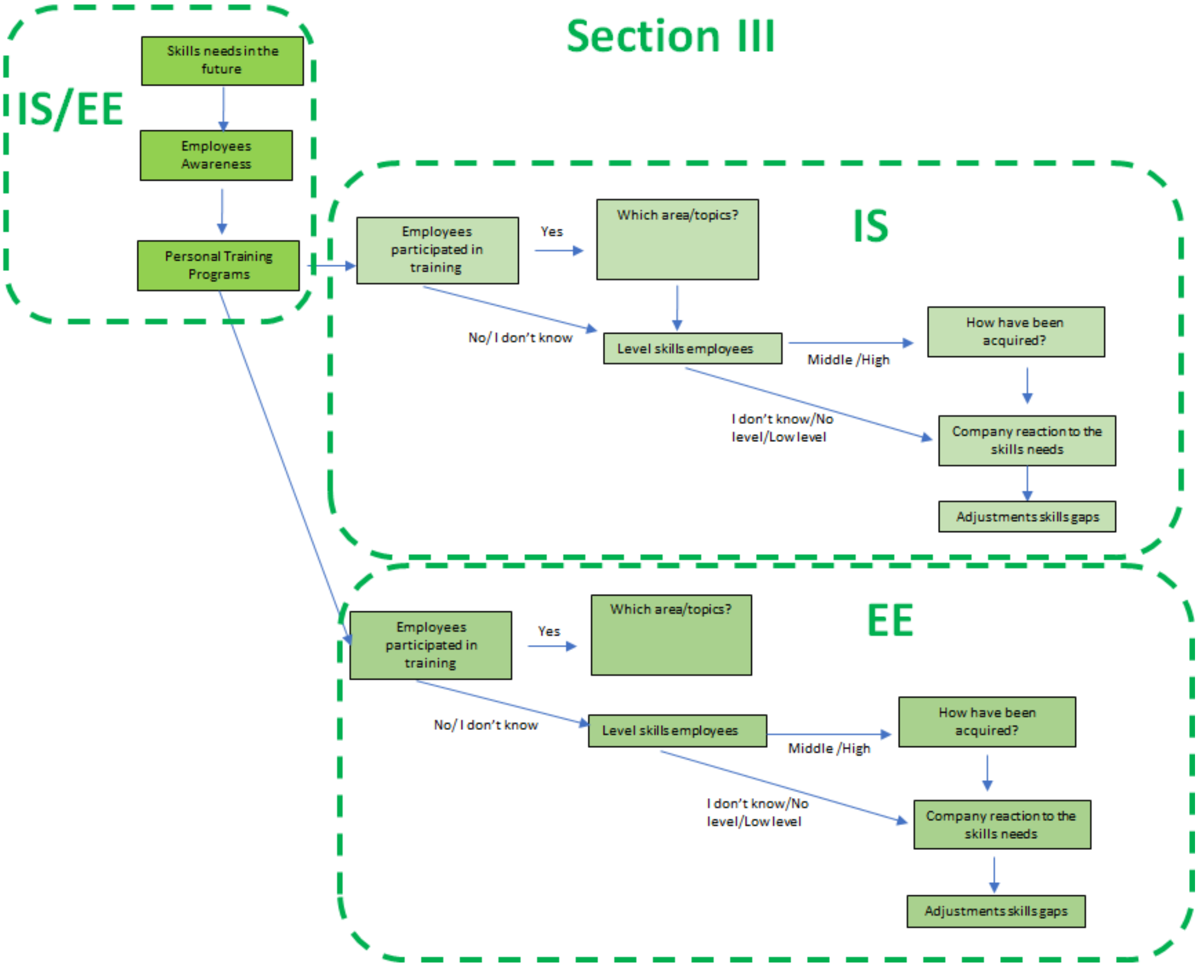

Figure 8.3: flow diagram of Section III of the online Questionnaire

8.2 Results of the survey

During the first phase survey's answers were collected by September 2020 the 25th while for the second phase they were collected by June 2022. In the first version of Deliverable 2.1 (due at end of September 2020) only 42 valid answers were available.

The number of accesses at the questionnaire were very consistent, more that 180, of which 81 recorded answers (in the second version of Deliverable 2.1) can be considered valid and meaningful in terms of completeness of the provided information, which have about doubled with respect of the size of the sample analysed in the first version of the deliverable.

The participants in the survey were recruited on a snowball basis, by sending the survey link to various people, who in turn disseminated it themselves. The resulting sample covers already a wide range of perspectives in terms of general information: country of origin of respondents, company size and product types.

The respondents are from companies located in several European countries. Most of the answers come from large enterprises, involving different professional profiles. The distribution of the compilers among the different sectors of process industry is shown in Figure 8.4, while Figure 8.5 depicts the geographical location of the participants to the survey.

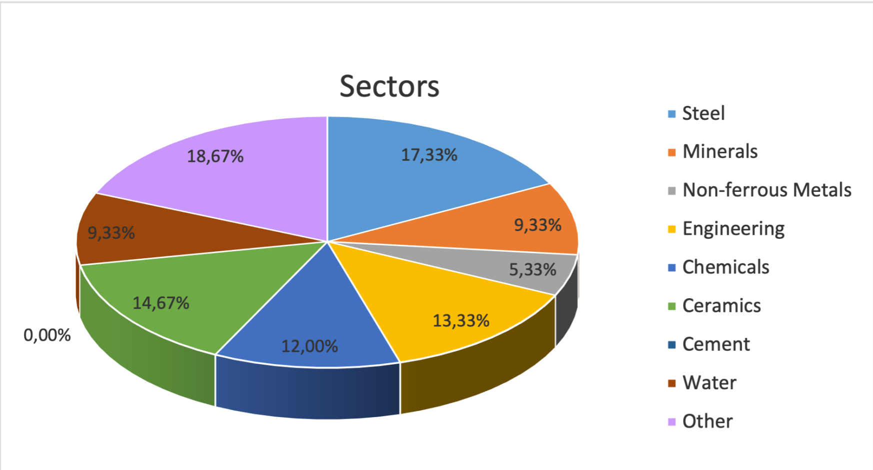

Figure 8.4: distribution of the compilers among the different sectors of process industry.

Figure 8.5: geographical distribution of the compilers.

According to the participants to the survey, the current level of implementation is higher for Energy Efficiency rather than for Industrial Symbiosis (see Figure 8.6), which is a quite natural, considering that the attention toward the second concept and its socio-economic value has increased in more recent times with respect to the first one. However, most of the compilers state that their company is going to emphasize its efforts in the future toward both the topics by also investing in technologies.

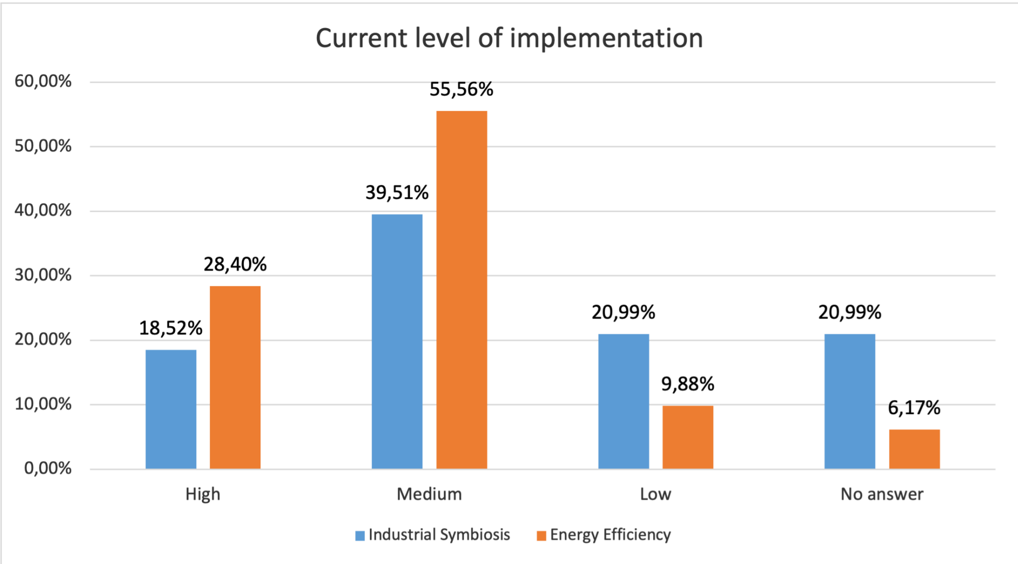

Figure 8.6: assessment of the current level of implementation of the two concepts.

Among the barriers faced by the companies in applying practices of Industrial Symbiosis, the most important ones appear to be cost of investments, integration of regional stakeholders, regulatory issues, outdated plants, infrastructure and equipment and cooperation challenges (see Figure 8.7).

Other barriers have been identified in administrative and regulatory issues related to material classification for transportation purposes, lack of real incentives for recycling of materials, lack of capability of industry to ensure a regular flow of material to recycle, difficulties in establishing a fair distribution of the benefits and costs across the partners, and maturity of financial tools and structures. To align investments in a complex structure such as Industrial Symbiosis is recognized as relevant risk. Finally, in national contexts, where SMEs dominate the industrial landscape, a further difficulty seems to be represented by the fact that SMEs have limited capabilities or are reluctant with respect to big investments in innovation/retrofitting, and, therefore, cooperative business models should be promoted.

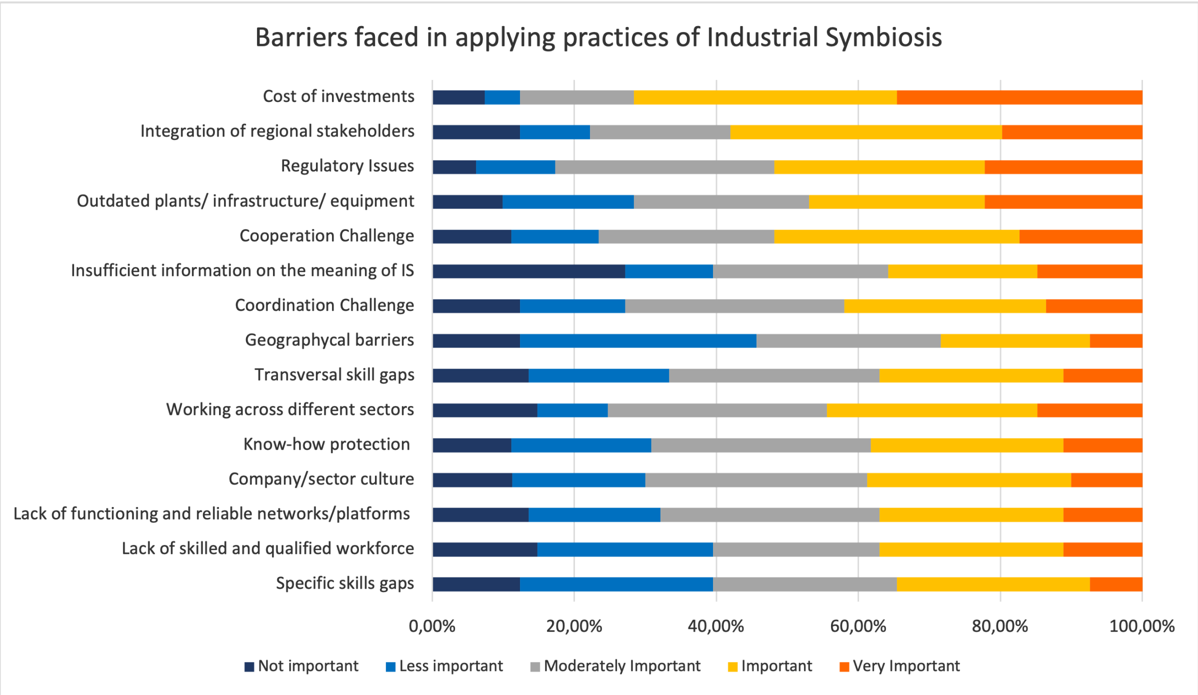

Figure 8.7: assessment of the barriers faced by companies in the application of practices of Industrial Symbiosis.

Among the barriers faced by the companies in applying practices of Energy Efficiency, the largely most relevant ones appear to be cost of investments and outdated plants, followed by cooperation challenges, working across different sectors and skills gaps (see Figure 8.8). Other barriers have been identified in the evolution of manufacturing and personnel habits as well as in the fact that the incorporation of solutions in a 24/7 brown field situation leads to disruptions and risks for continuous production.

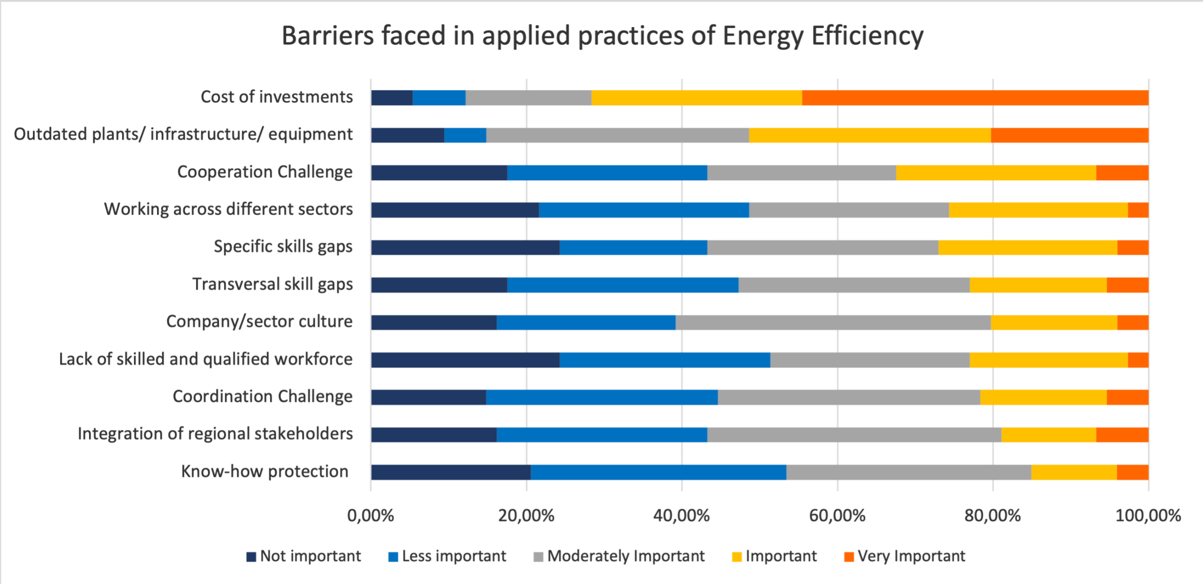

Figure 8.8: assessment of the barriers faced by companies in the application of practices of Energy Efficiency.

The main economic benefits, which are expected from the application of practices form Industrial Symbiosis, are reduction of costs for waste disposal, increased sustainability of the production process as well as increased overall competitiveness. Among other economic benefits, the reduction of water consumption has been highlighted (which is beneficial for the environment as well). On the other hand, the application of Energy Efficiency practices is expected to provide higher benefits in terms of overall energy efficiency, increased sustainability and increased competitiveness, such as depicted in Figure 8.9.

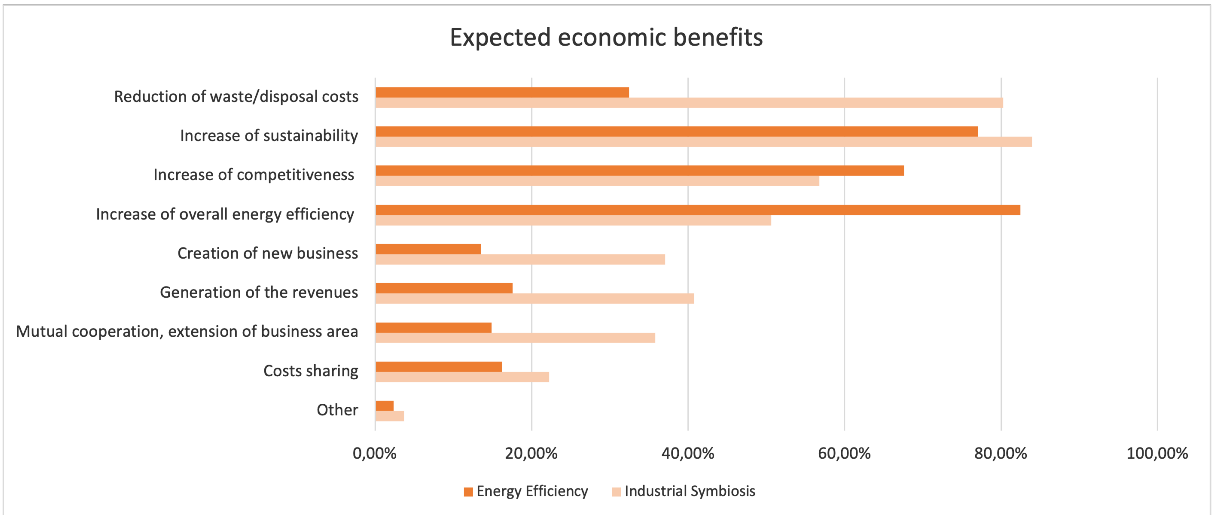

Figure 8.9: Expected economic benefits for the companies from the application of practices of Industrial Symbiosis and Energy Efficiency. The x axis refers to the percentage of the participants who selected the benefits (multiple choice are allowed).

From the environmental point of view, Industrial Symbiosis is expected to mostly lead to reduction of wastes, while Energy Efficiency is expected to mostly lead to reduction of greenhouse gases emissions. However, both concepts are also expected to contribute to reduction of natural resources depletion and of ecological pressure on the planet (see Figure 8.10).

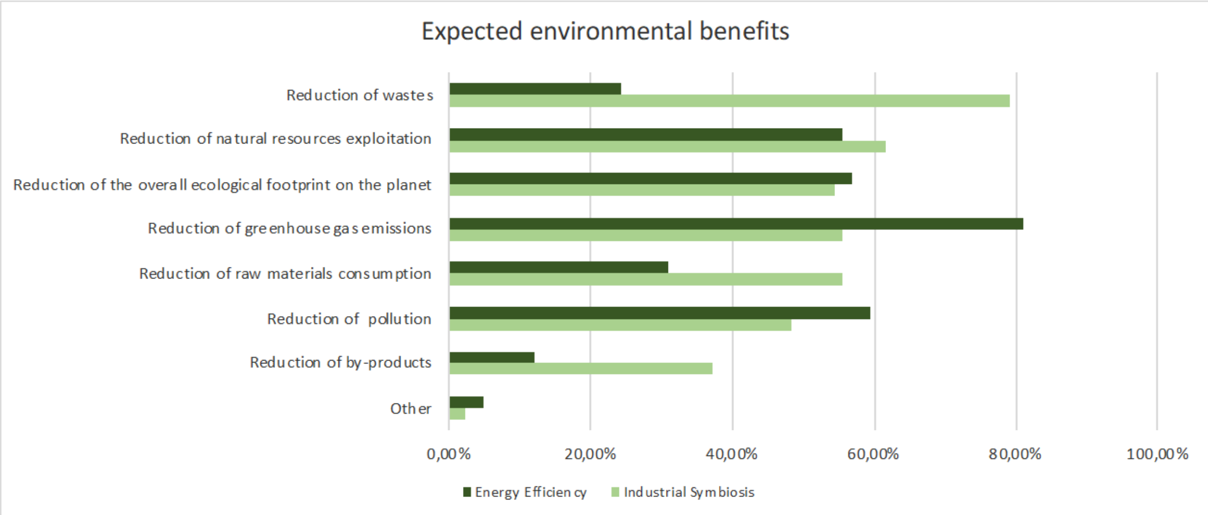

Figure 8.10: Expected environmental benefits for the companies from the application of practices of Industrial Symbiosis and Energy Efficiency. The x axis refers to the percentage of the participants who selected each benefit (multiple choices are allowed).

Finally, form the social point of view, both Industrial Symbiosis and Energy Efficiency are expected to lead benefits on green skills and improvement of workers' performance for the companies, but higher expectations are put on Energy Efficiency related to creation of new jobs and improvement of working conditions (see Figure 8.11).

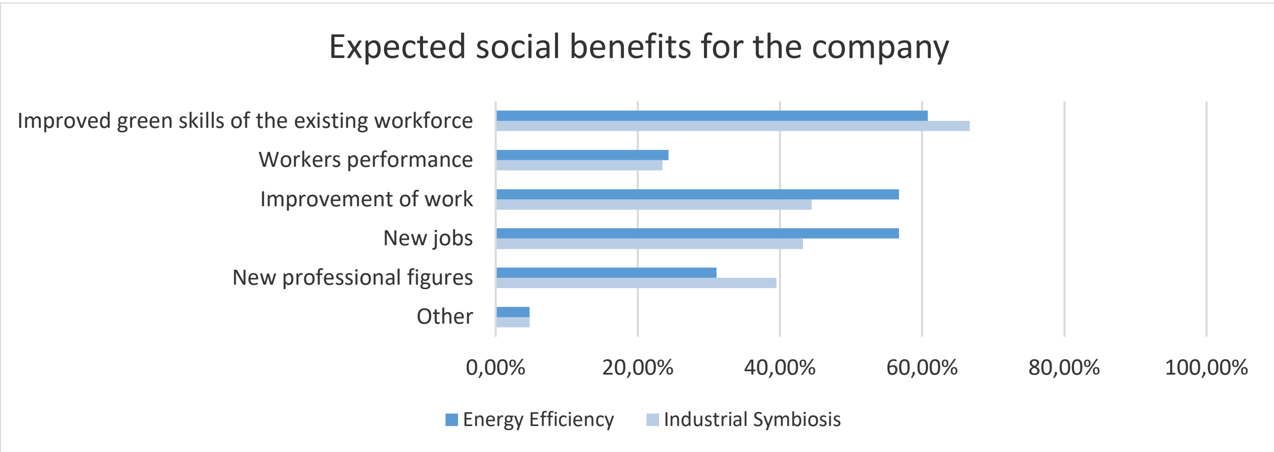

Figure 8.11: Expected social benefits for the companies from the application of practices of Industrial Symbiosis and Energy Efficiency. The x axis refers to the percentage of the participants who selected each benefit (multiple choices are allowed).

Other benefits are expected from industrial Symbiosis in the improvement of the overall perception of industry in the society, while Energy Efficiency is expected to lead to reduction in the global environmental impact.

Similar social benefits deriving from the application of the principles of Industrial Symbiosis and Energy Efficiency are also perceived by the participants in the company's region: more than half of them highlight expectations concerning reduction of local environmental impact, new jobs and benefits to the present and future community.

The compilers, whose company is already involved in practices of Industrial Symbiosis or Energy Efficiency, consider that all the resource synergies are significantly affected by Industrial Symbiosis, while Efficiency mostly affects energy flows, although it has a non-negligible effect on the other flows. Among other involved resources synergies, water and CO_2 have also been identified as relevant for Industrial Symbiosis (see Figure 8.12).

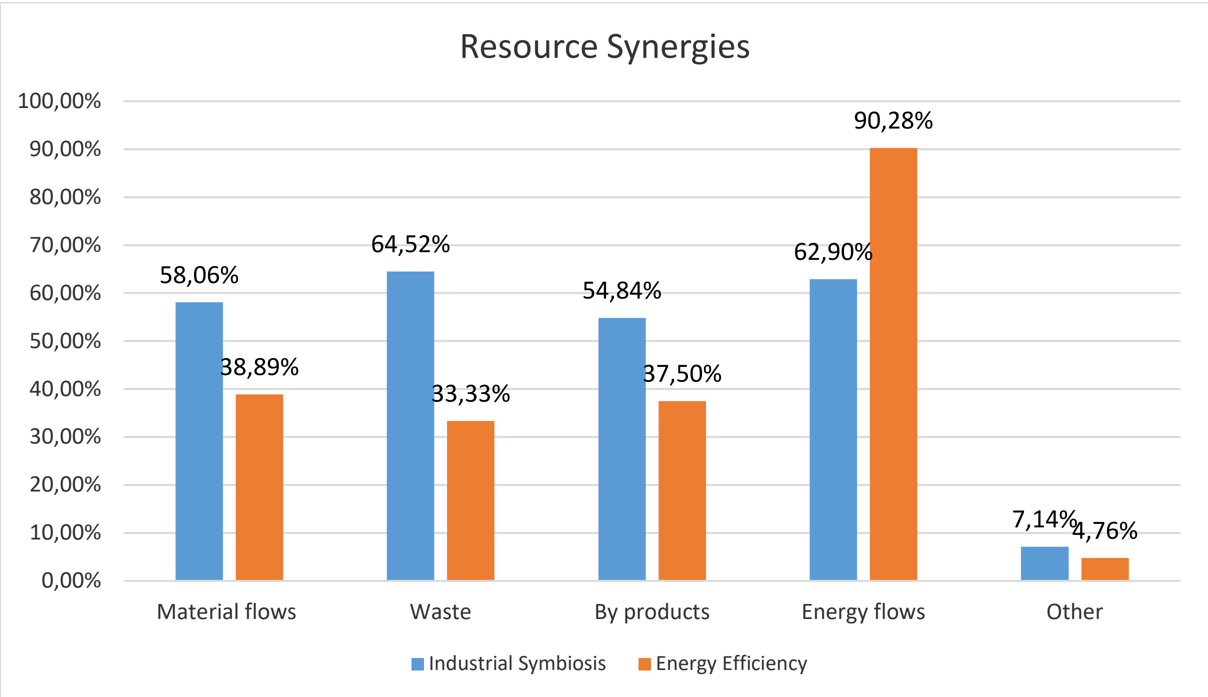

Figure 8.12: Resource synergies involved in the application of practices of Industrial Symbiosis and Energy Efficiency. The y axis refers to the percentage of the participants who selected each resource (multiple choices are allowed).

Among the tools and technologies, which can be adopted for the implementation of practices of Industrial Symbiosis or Energy Efficiency, Process Technologies and Digital technologies are most frequency indicated as useful, by the compilers, whose company is already involved in such practices. ICT tools are indicated as more relevant for Energy Efficiency and by-products treatment technologies as more relevant for Industrial Symbiosis (see Figure 8.13).

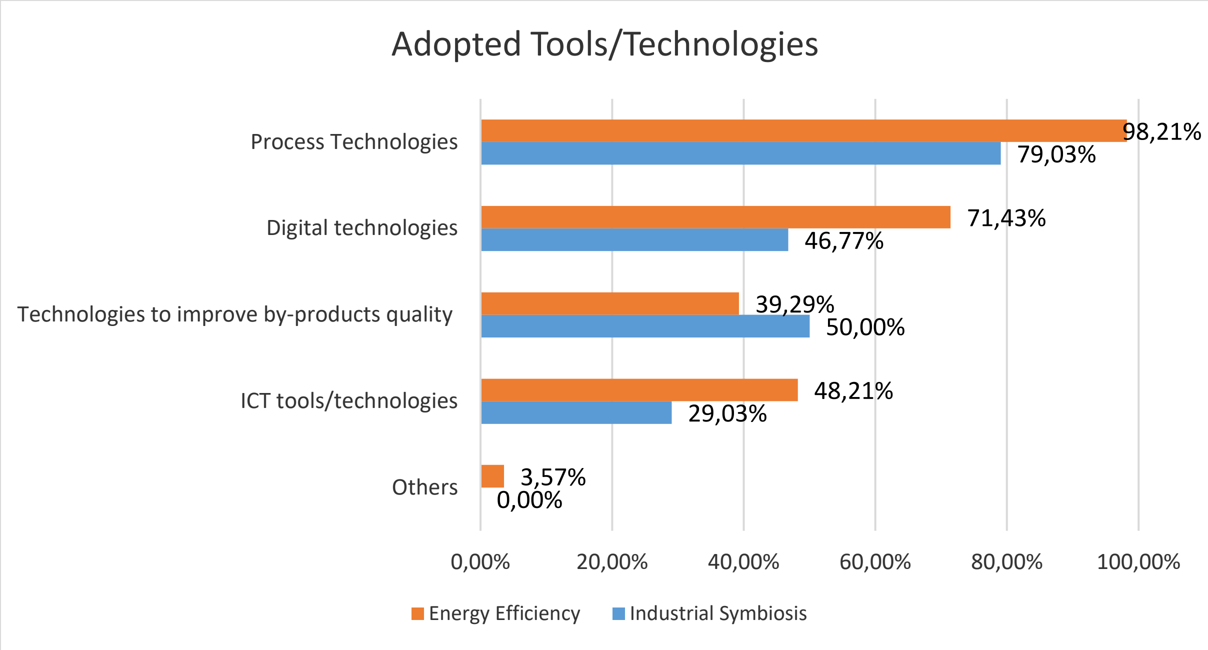

Figure 8.13: main tools/technologies adopted for the implementation of Industrial Symbiosis and Energy Efficiency. The x axis refers to the percentage of the participants who selected each tool (multiple choices are allowed).

The main actors, which are indicated as involved in Industrial Symbiosis and Energy Efficiency practices are the internal actors, but also other industries are considered by more than half of the participants. Local actors are also taken into account, although they are considered more involved in Energy Efficiency rather than in Industrial Symbiosis, and other actors are identified as regulators (see Figure 8.14).

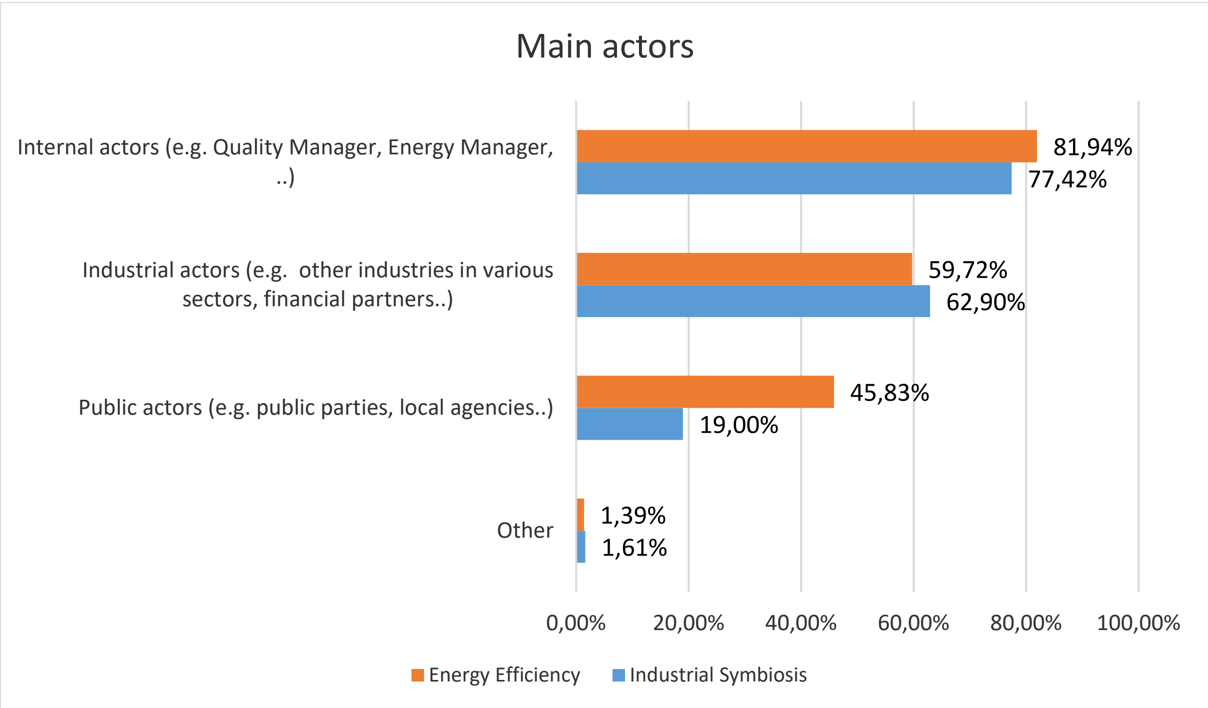

Figure 8.14: main actors involved in the implementation of Industrial Symbiosis and Energy Efficiency. The x axis refers to the percentage of the participants who selected each actor (multiple choices are allowed).

The areas of the company where Industrial Symbiosis and Energy Efficiency are mostly applied are the Production process chain and the Energy Department, but also the Environmental and Sustainability department appear to be significantly involved, especially as far as Industrial Symbiosis is concerned (see Figure 8.15).

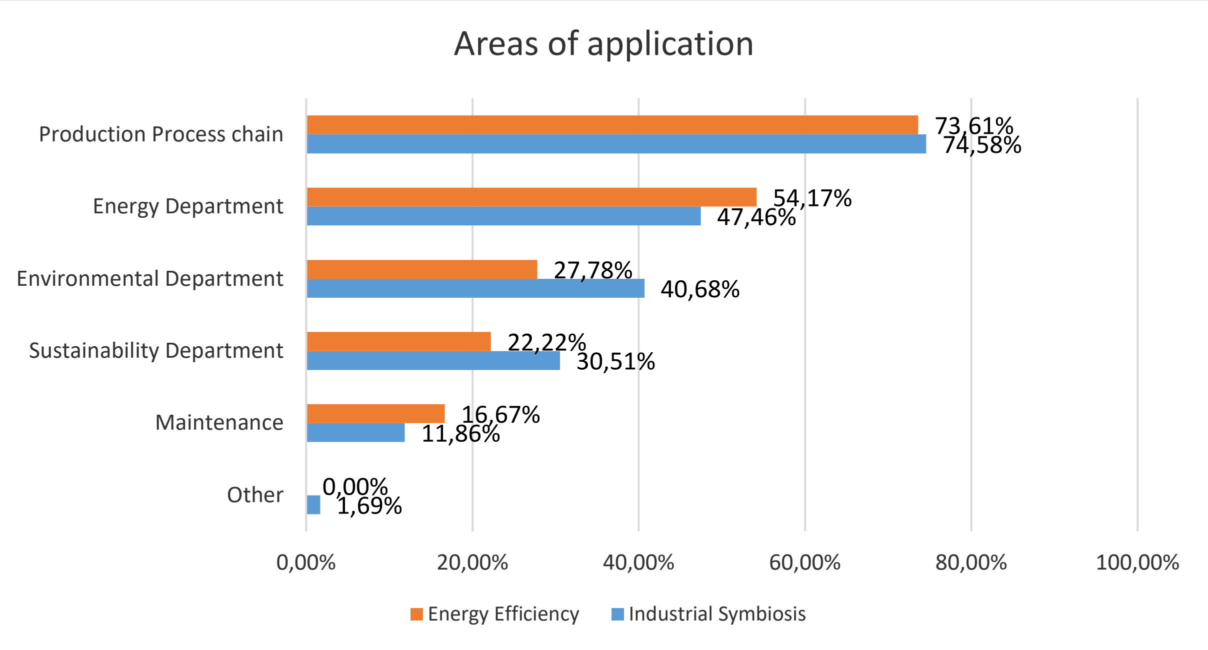

Figure 8.15: main areas of application of Industrial Symbiosis and Energy Efficiency in the company. The x axis refers to the percentage of the participants who selected the areas (multiple choices are allowed).

As far as the impact of the on the workforce in the incoming 3-5 years in those companies, which are planning to introduce or more actively apply Industrial Symbiosis and Energy Efficiency practices in the future, mostly an increase of jobs and especially highly qualified profiles is expected (see Figure 8.16). Other impacts have been identified in new research directions for development of emerging technologies including digital processing methods (e.g. additive manufacturing, use of recycled materials for high tech applications) and digital technologies, attraction of young talents and development of new business lines, but also higher workload.

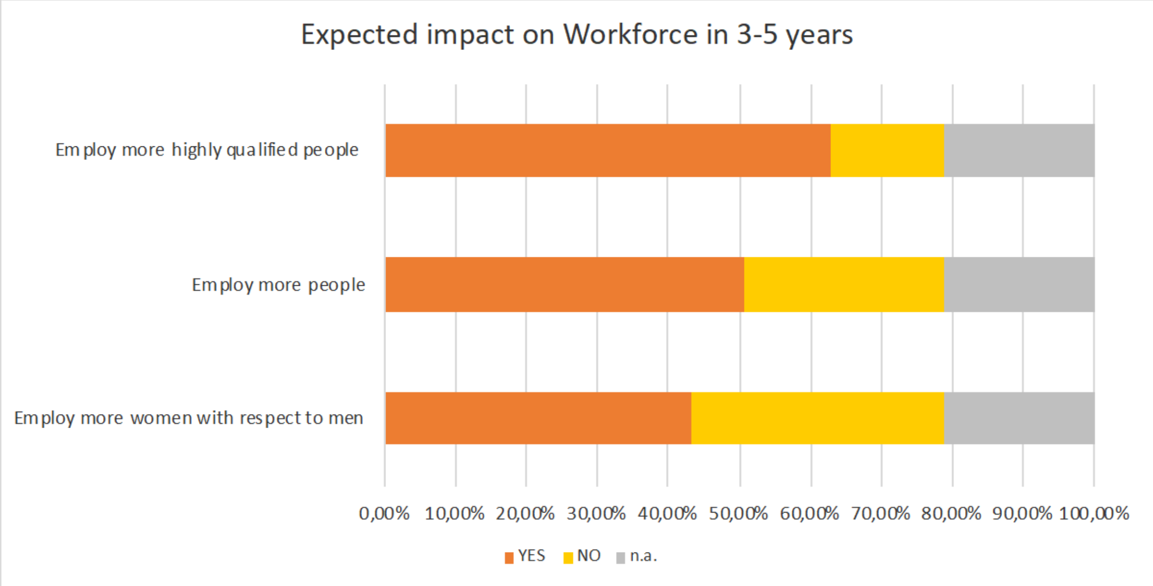

Figure 8.16: expected impact of application of Industrial Symbiosis and Energy Efficiency on the workforce of the company.

The skills that will mostly need to be updated in the incoming 3-5 years are identified in specific job-related skills, digital and personal skills (see Figure 8.17). Other skills identified are regulatory skills and entrepreneurship.

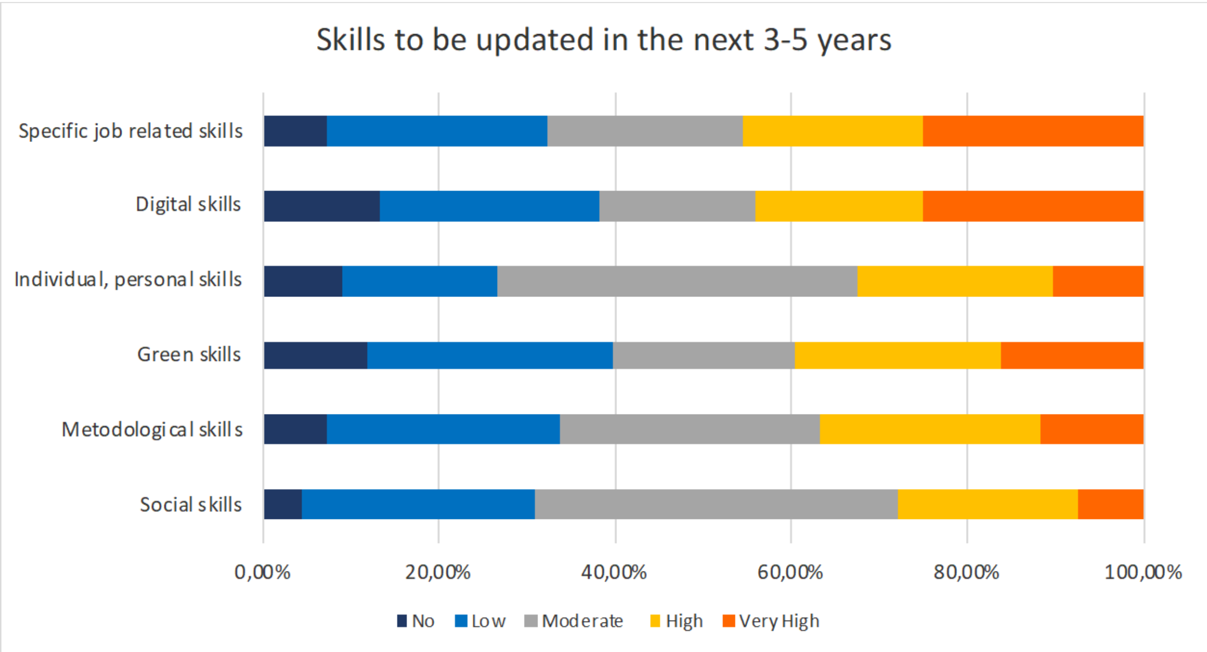

Figure 8.17: needs for skills updating for the application of Industrial Symbiosis and Energy Efficiency.

Among the different working categories, Managers and Technicians are considered more aware of the needs of Industrial Symbiosis with respect to Employees, while for Energy Efficiency in average more than 50% of the workers in all the categories are considered aware and such percentage is particularly high for Managers (see Figure 8.18). Noticeably, the awareness of the needs of Energy Efficiency is higher that the awareness of the needs of Industrial Symbiosis.

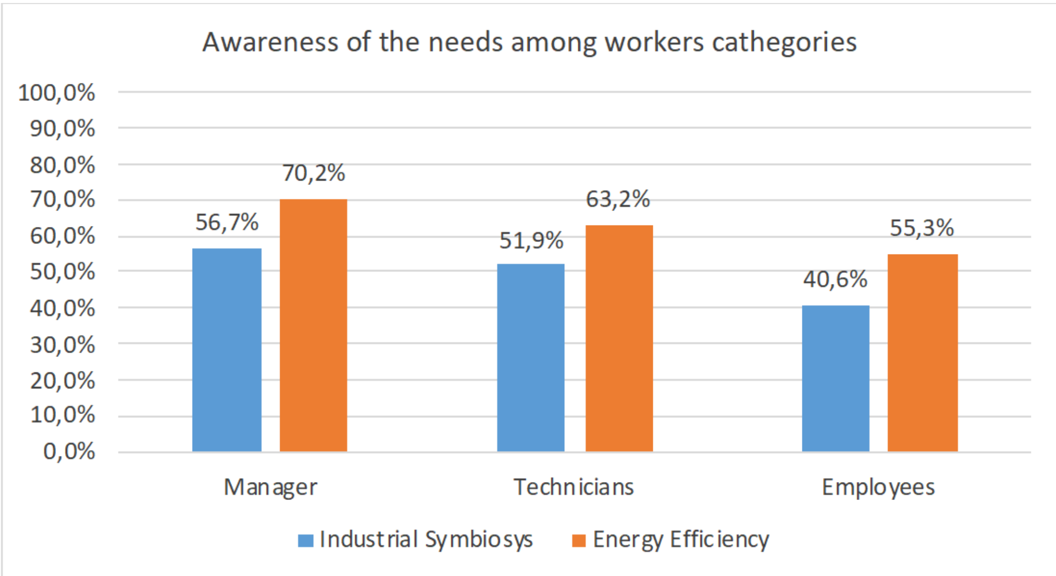

Figure 8.18: Average percentage of workers belonging to different categories, which are aware of the needs of Industrial Symbiosis and Energy Efficiency among the different categories.

Most of the participants to the survey state that that no specific training programs exist especially on Industrial Symbiosis but also (although at a lower degree) on Energy Efficiency (see Figure 8.19). In particular, about 47% of the applicants state that no employee of their company participated in trainings that strengthened her/his skills or provided knowledge related to Industrial Symbiosis over the last 12 months, while only about 26% of them state the same thing concerning Energy Efficiency.

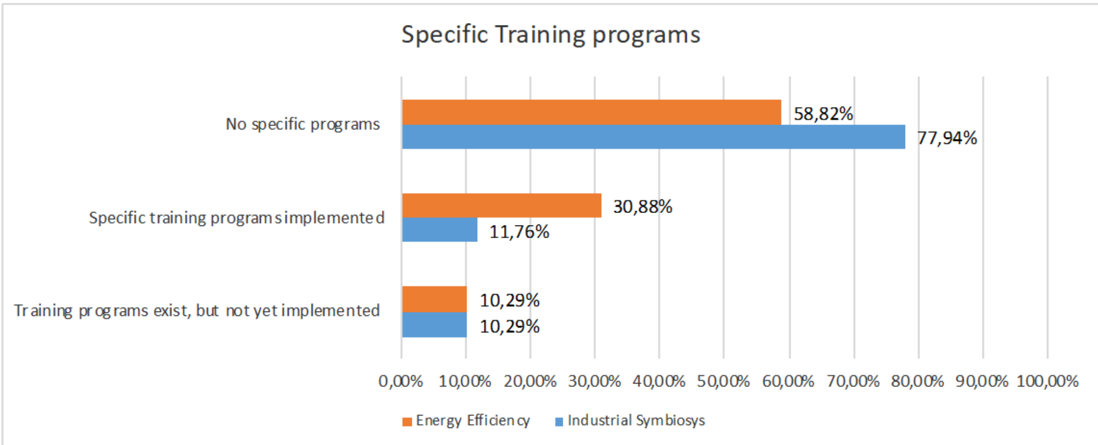

Figure 8.19: Implementation of specific training programs on Industrial Symbiosis and Energy Efficiency.

The level of skill of the employee of the company is stated to be generally lower for Industrial Symbiosis than for Energy Efficiency (see Figure 8.20).

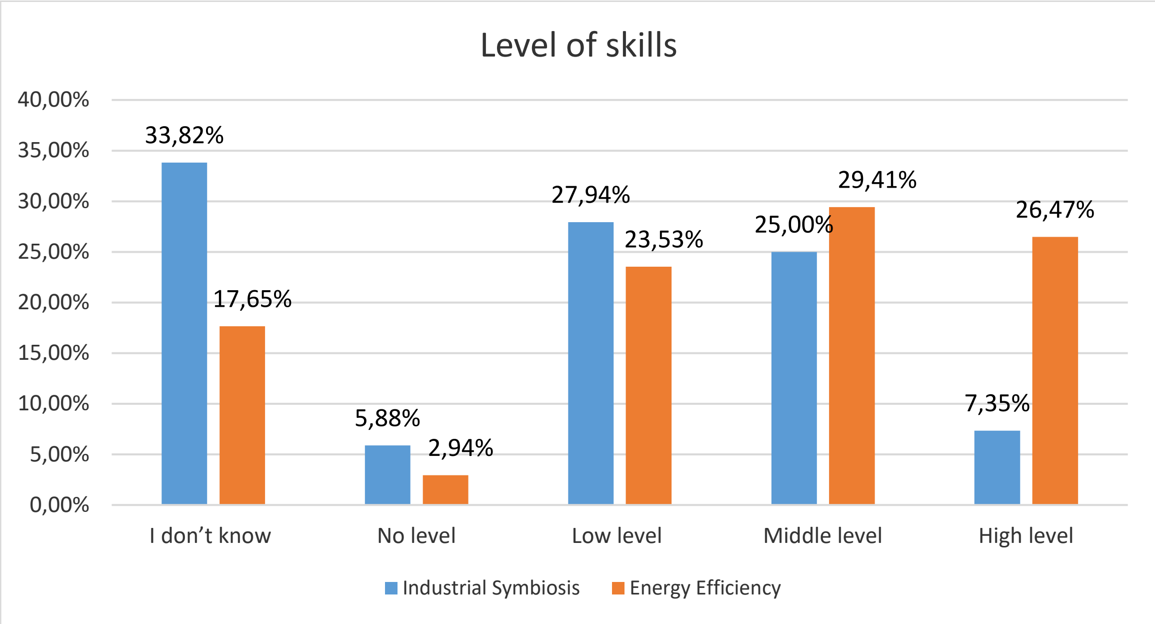

Figure 8.20: Perceived level of skills of the company's employee on Industrial Symbiosis and Energy Efficiency.

Among the participants who stated that the level of skill of the employees is Middle or High, training on the job and non-formal training are considered the most common means to improve skills (see Figure 8.21). In particular, none of the participants stated that the employees received skills related to Industrial Symbiosis through formal VET process.

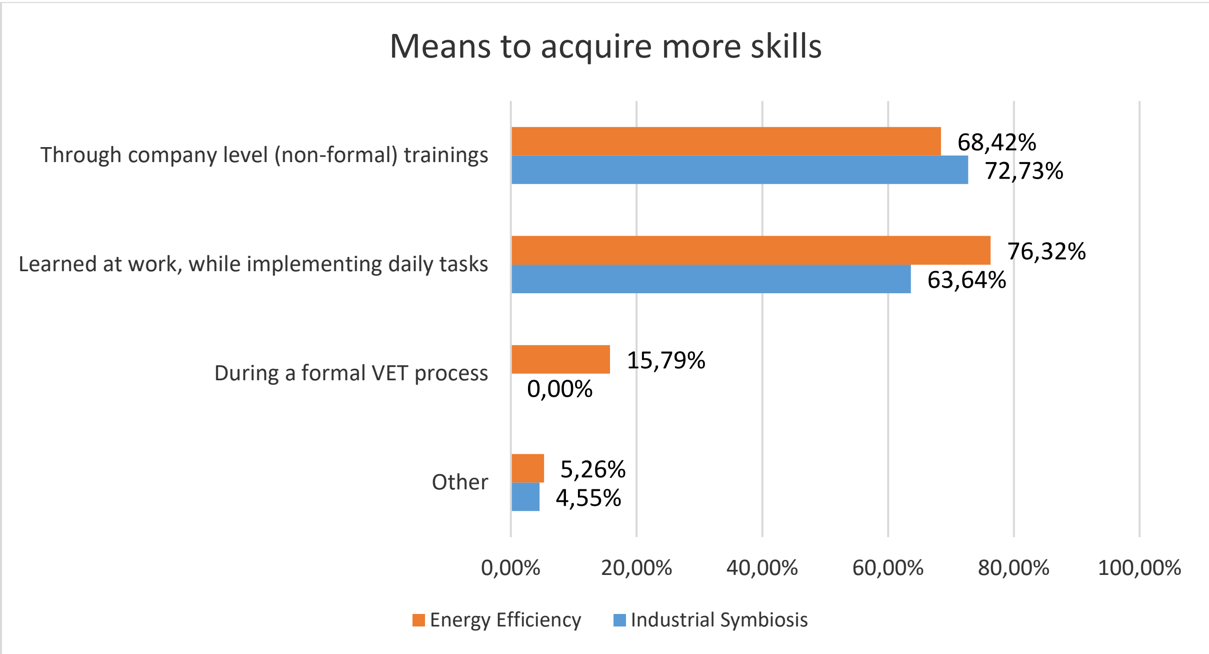

Figure 8.21: adopted means to acquire skills on Industrial Symbiosis and Energy Efficiency. The x axis refers to the percentage of the participants who selected each training procedure (multiple choices are allowed).

It is perceived that a relevant skill demands is being faced because of Industrial Symbiosis for any workers category, although such demand is slightly higher for Technicians (see Figure 8.22).

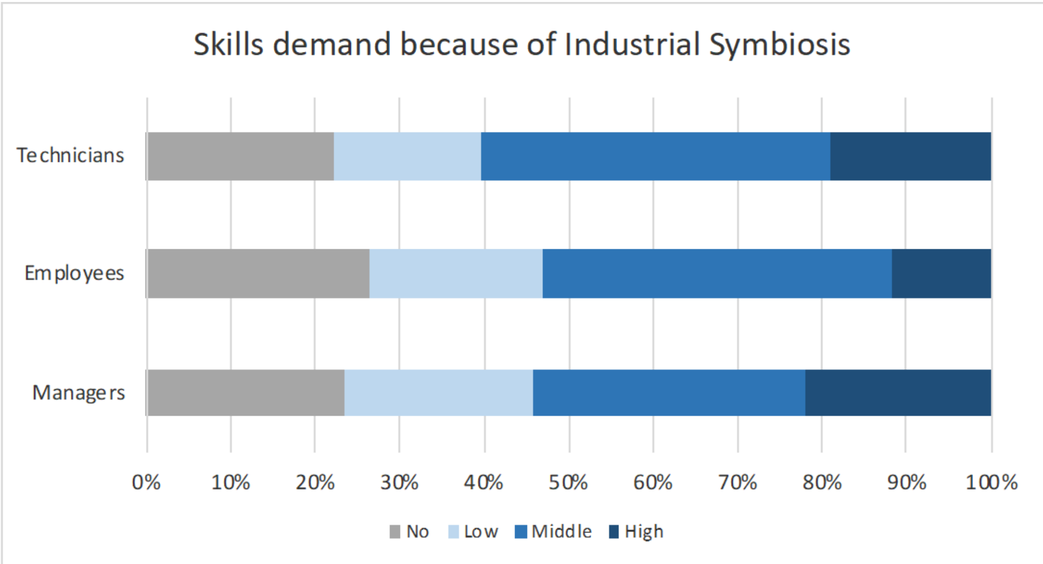

Figure 8.22: perceived skill demands because of Industrial Symbiosis.

The applicants consider that main means to adjust the above-mentioned skill gaps are training measures, both internal and external (see Figure 8.23). A further identified means consists in training on the job.

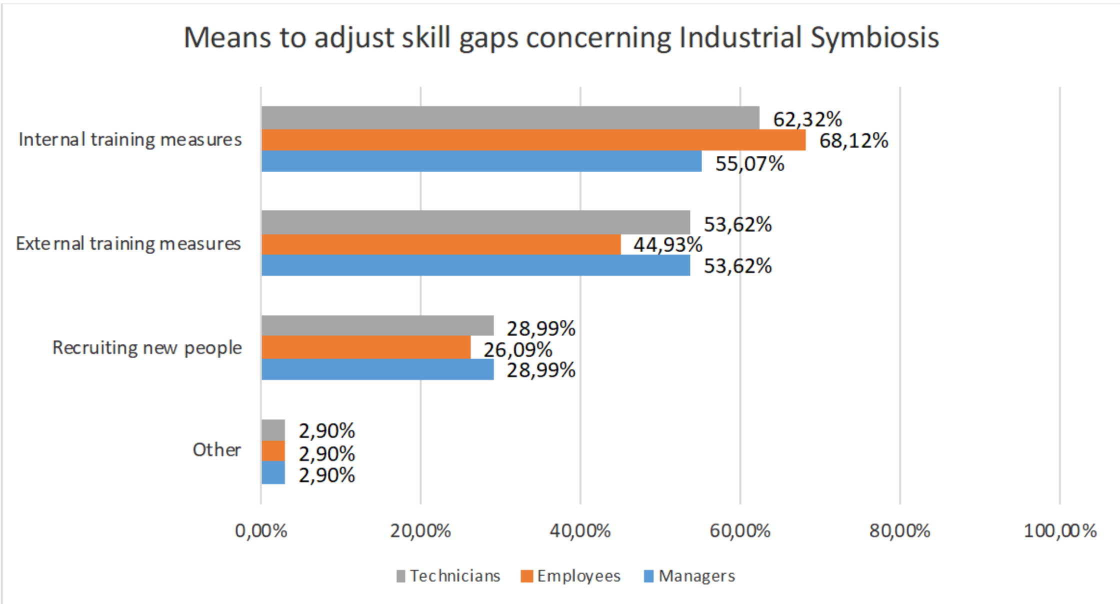

Figure 8.23: means to adjust skill gaps related to Industrial Symbiosis. The x axis refers to the percentage of the participants who selected each means (multiple choices are allowed).

As far as Energy Efficiency is concerned, the skill demands being faced by companies are considered relevant for any workers category, although such demand is slightly higher for Managers (see Figure 8.24), and also in this case, the main means to adjust the skill gaps are training measures, both internal and external (see Figure 8.25).

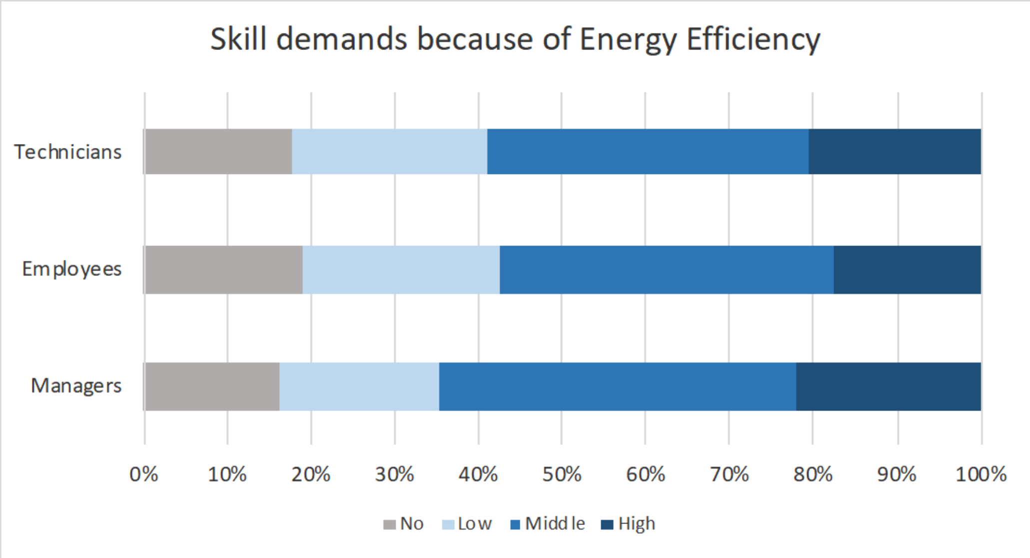

Figure 8.24: perceived skill demands because of Energy Efficiency.

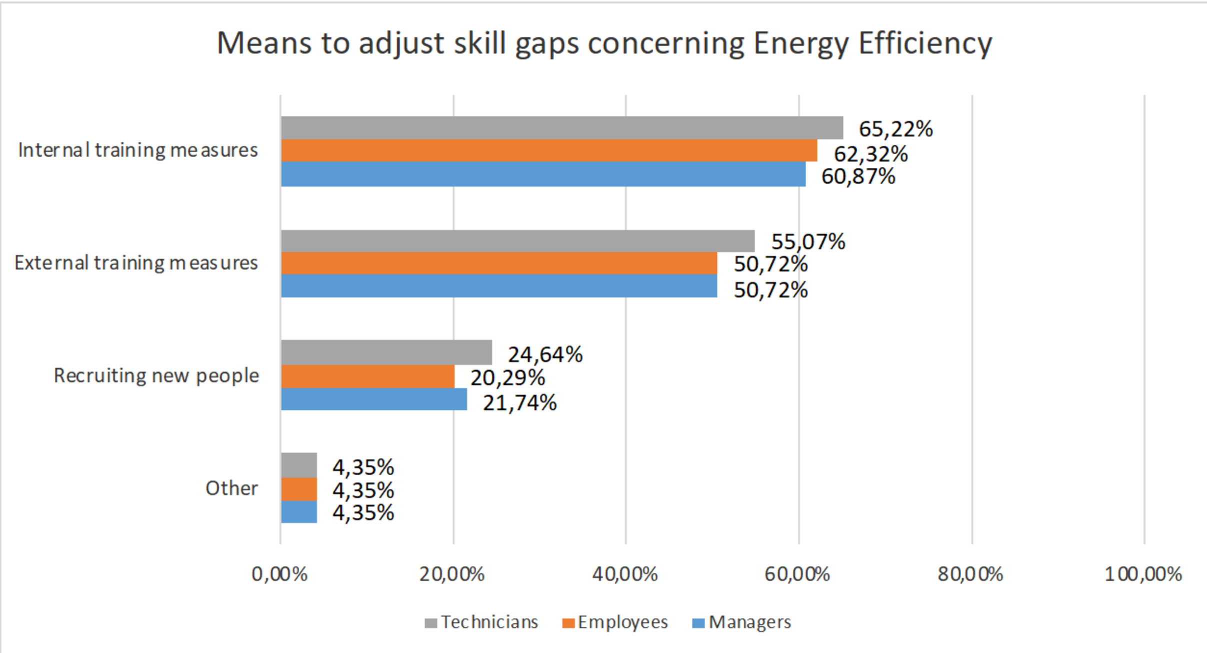

Figure 8.25: means to adjust skill gaps related to Energy Efficiency The x axis refers to the percentage of the participants who selected each means (multiple choices are allowed).

8.3 Conclusions of the survey

Industrial Symbiosis and Energy Efficiency are receiving increasing attention in the companies and are perceived as an opportunity for companies, as they can lead to many different kind of benefits. However, the barriers to the implementation of such concepts are high, not all the personnel is aware of the needs related to the and the implementation of practices and solutions concerning both Industrial Symbiosis and Energy Efficiency are perceived to generate skill demands in any category of workers.

Going into more details, it appears that the current level of implementation is higher for EE rather than for IS, although companies perceive IS and EE as an opportunity and are going to emphasize their efforts in the future toward both the topics. Moreover, some barriers resulted in the implementation practices and perception of solutions to generate skill demands in any category of workers. In particular, according to the participants to the survey, for IS the main barriers are:

- cost of investments;
- integration of regional stakeholders,
- regulatory issues;
- outdated plants, infrastructure and equipment;
- cooperation challenges

For EE the main barriers are:

- cost of investments;
- outdated plants;
- cooperation challenges;
- working across different sectors;
- skills gaps.

The level of skill of the employee of the company is stated to be generally lower for IS than for EE. In addition, the current training measures implemented by companies are mostly not formal and unstructured (e.g. training on the job) and the emerging and future skill gaps will be overcame by internal and external training activities. The skills that will mostly need to be updated in the incoming 3-5 years are identified in specific job-related skills, digital and personal skills. Other useful skills identified within the survey are regulatory skills and entrepreneurship. Therefore, an initiative such as those pursued within the SPIRE-SAIS project appear to be fully in line with the expectations and demands of the participants to the survey.

The answers to the questionnaire, which were collected after the delivery of Deliverable 2.1, mostly confirmed the outcomes which were already shown is such deliverable.

9 References

(s.d.). Tratto da http://www.international-synergies.com/wp-content/uploads/2015/10/G7-Arden_Clarke-10-Year-Framework-Programme-for-SCP.pdf] [http://www.international-synergies.com/wp-content/uploads/2015/10/G7-Laybourn-International-Synergies.pdf

(s.d.). Tratto da http://www.international-synergies.com/wp-content/uploads/2015/10/G7-Arden_Clarke-10-Year-Framework-Programme-for-SCP.pdf

European Commission. (2019). *The European Green Deal; Communication No. 640.* Brussels, Belgium: Commission of European Communities.

(EIT-KIC), E.-I. (Climate KIC, 2012-2013). *EUR-IS (EIT-KIC).* Tratto da https://eit.europa.eu/activities/innovation-communities

(Grant agreement ID: 636834, H.-E. 2.-2. (s.d.). Integrated Process Control based on Distributed In-Situ Sensors into Raw Material and Ener-gy Feedstock. *https://cordis.europa.eu/project/id/636834*.

2, I. S. (s.d.). Tratto da http://www.international-synergies.com/wp-content/uploads/2015/10/G7-Laybourn-International-Synergies.pdf

3GF. (Global Green Growth Forum, 2013-2016). *3GF Industrial Symbiosis Public Private Partnership Track.* Tratto da http://www.greengrowthknowledge.org/organization/global-green-growth-forum-3gf

4REFINERY. (Project reference: 727531, 01/05/2017 to 30/04/2021). *Scenarios for integration of bio-liquids in existing REFINERY processes.*

5REFRACT. (2018-2020). *LIFE 17 ENV/ES/000228, 5REFRACT.* Tratto da https://www.life5refract.eu/en

820670, G. a., H2020-EU.2.1.5.3, & 2018-2022. (s.d.). Innovative and efficient solution, based on modular, versatile, smart process units for energy and resource flexibility in highly energy intensive processes . *https://cordis.europa.eu/project*.

A. Wolff, F. M. (2019). "Economical Mixed-Integer Model Predictive Controller for optimizing the sub-network of the BOF gas,". *European Steel Days ESTAD June 24-28 2019.* Dusseldorf (Germany).

Abdi-Oskouei, M., & Awuah-Offei, K. (2018). Role of the operator in dragline energy efficiency. In *Energy Efficiency in the Minerals Industry* (p. 181-194). Springer, Cham.

Abele, E. C. (2016). ETA learning factory: A holistic concept for teaching energy efficiency in production. *Procedia CIRP* , 83.

ACASOS. (RCFS-CT-2007-00003; 01/07/2007-31/12/2010). *Alternate carbon sources for sintering of iron ore.*

ACTISLAG. (RFCS-CT-2017- 749809; 1/07/2017- 31/12/2020). *New Activation Routes for Early Strength Development of Granulated Blast Furnace Slag.*

ADAPTEAF. (RFSP-CT-2014-00004 01/07/2014-30/06/2017). *Adaptive on-line control of the EAF based on innovative sensors and comprehensive models for.*

ADVANCE. (RFCS; 01/09/2023-31/08/2025). *Accompanying measure for Dissemination, Valorisation and Collaborative Exploitation of circularity of constructional steel products.* https://www.steelconstruct.com/eu-projects/advance/.

Agency, I. E. (2009). *Cement Technology Roadmap.*

AHEAD. (Romania's National Recovery and Resilience Plan; 01/07/2023-30/06/2026). *Antimicrobial High-Entropy Alloys and Coatings with Enhanced Physical and Mechanical Properties Designed* *by Machine-Learning Assisted Methods for Mitigation of Microbiologically Influenced Corrosion.* https://imnr.ro/ahead/.

Akyazi, T., Goti, A., Alberdi, E., Behrend, C., Schroder, A. J., Colla, V., . . . Weinel, M. (2024). Conclusion: Recasting the future of the European steel industry. In *In Industry 4.0 and the Road to Sustainable Steelmaking in Europe: Recasting the Future* (p. 219-227). Cham: Springer International Publishing.

Akyazi, T., Goti, A., Oyarbide-Zubillaga, A., Alberdi, E., Carballedo, R., Ibeas, R., & Garcia-Bringas, P. (2020). Skills Requirements for the European Machine Tool Sector Emerging from Its Digitalization. *Metals*, 1665.

Akyazi, T., Oyarbide, A., Goti, A., Gaviria, J., & Bayon, F. (2020). Creating a roadmap for professional skills in industry 4.0. *Hydrocarb. Process*.

Alcamisi, E. M. (2015). Process integration solutions for water networks in integrated steelmaking plants. *Chemical Engineering Transactions, 45*, 35-42.

ALCHIMIA. (Horizon.2.4-Digital, Industry and Space; 01/09/2022-31/08/2025). *Data and decentralized Artificial intelligence for a competitive and green European metallurgy industry.* https://cordis.europa.eu/project/id/101070046.

Alnadish, A., & Aman, Y. (2018). A study on the economic using of steel slag aggregate in asphalt mixtures reinforced by aramid fiber. *Arpn J. Eng. Appl. Sci. , 13*, 276–292.

AlSiCal. (H2020/2014-2020 under grant agreement n° 820911, 2019-2023). *Towards sustainable mineral and metal industry: ZERO Bauxite Residue and ZERO CO2 from coproduction of Alumina, Silica and precipitated Calcium carbonate by the Aranda-Mastin technology.* Tratto da https://www.alsical.eu/

ALTERAMA. (RFCR-CT-2014-00006; 01/07/2014-31/12/2017). *Developing uses of alternative raw materials in cokemaking.*

Aluminium, E. (2020). *EU Strategies on Energy Sector Integration & Hydrogen.* Tratto da https://www.european-aluminium.eu/media/2945/16-06-2020-european-aluminium-on-eu-energy-sector-integration-hydrogen-strategy-policy-roadmaps.pdf

Aluminium, E. (2021). *ALUMINIUM IN ACTION SHAPING SOLUTIONS FOR A SUSTAINABLE SOCIETY.* Tratto da https://www.european-aluminium.eu/media/3429/2022-01-25-european-aluminium_sustainability-mid-term-review.pdf.

Aluminium, E. (2021). *Our proposals to the EU's "fit for 55% package-For a low-carbon, circular and green aluminium industry in Europe.* Tratto da https://www.european-aluminium.eu/media/3178/2021-05-25-european-aluminium-position-paper-on-the-fit-for-55-package.pdf

Aluminium, E. (2023). *Critical Raw Materials Act.* Tratto da https://european-aluminium.eu/wp-content/uploads/2023/04/2023-03-30-CRMA-European-Aluminium-Position-paper.pdf

Aluminium, R. a. (2023). *Net-zero by 2050: Science-Based Decarbonisation Pathways for the European Aluminium Industry.* Tratto da https://european-aluminium.eu/blog/netzeroby2050/

AMITIE. (2017-2021). *H2020, MSCA-RISE-2016, AMITIE - ADDITIVE MANUFACTURING INITIATIVE FOR TRANS-NATIONAL INNOVATION IN EUROPE.* Tratto da https://cordis.europa.eu/project/id/734342

Ammenberg, J. B. (2015). Improving the CO2 performance of cement, part III: the relevance of industrial symbiosis and how to measure its impact. *Journal of Cleaner Production*, 145-155.

Ammenberg, J., Roozbeh , F., Helgstrand, A., Eklund, M., & Baas, L. (2011). *Industrial symbiosis for improving the CO2-performance of cement production." Final report of the CEMEX-Linköping University industrial ecology project.*

An energy recovery apparatus suitable for heat treatment of fluids or solids ;us2012184797 (a1);19/07/2012; us8969647 (b2) 03/03/2015. (s.d.). Tratto da https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2011042927

Andersson, A., Andersson, M., Mousa, E., Kullerstedt, A., Ahmed, H., Björkman, B., & Sundqvist-Ökvist, L. (2018). The potential of recycling the high-zinc fraction of upgraded BF sludge to the desulfurization plant and basic oxygen furnace. *Metals , 8*, 1057.

Ansari, N. (2017). Innovation through Recycling/Minimizing Waste. *Innovation Forum.* Oxford, UK.

Antonazzo, L., Stroud, D., Weinel, M., Dearden, K., & Mowbray, A. (2021). *Preparing for a just transition: meeting green skills needs for a sustainable steel industry.* Tratto da https://orca.cardiff.ac.uk/145353/

Arens, M., Åhman, M., & Vogl, V. (2021). Which countries are prepared to green their coal-based steel industry with electricity?-Reviewing climate and energy policy as well as the implemen-tation of renewable electricity. *Renewable and Sustainable Energy Reviews*, 110938.

Arjen, H. (2015). *The water footprint of industry.* Assessing and Measuring Environmental Impact and Sustainability.

Asaoka, S., Okamura, H., Morisawa, R., Murakami, H., Fukushi, K., Okajima, T., . . . Ohta, T. (2013). Removal of hydrogen sulfide using carbonated steel slag. *Chem. Eng. J.*(228), 843–849.

ASCER. (s.d.). *Spanish Ceramic Tile manufacturers Association* . Tratto da https://ascer.es/ascerPresentacion.aspx?lang=en-GB&cual=presentacion: https://ascer.es/ascerPresentacion.aspx?lang=en-GB&cual=presentacion

Ashton, W. S. (2017). Life and death of industrial ecosystems. *Sustainability (Switzerland)*, 1-15.

ASTRABAT. (H2020; 2020-2023). *ASTRABAT*. Tratto da https://astrabat.eu/

ATHOR. (2017-2019). *H2020, agreement n. 764987, ATHOR –ADVANCED THERMOMECHANICAL MULTISCALE MODELLING OF REFRACTORY LININGS.* Tratto da www.etn-athor.eu

Atmaca, A. Y. (2014). Analysis of the parameters affecting energy consumption of a rotary kiln in cement industry. *Appl. Therm. Eng.*, 435-444.

Axelson, M., Oberthür, S., & Nilsson, L. J. (2021). Emission reduction strategies in the EU steel industry: Implications for business model innovation. *Journal of Industrial Ecology*, 390-402.

Ažman Momirski , L., Mušič, B., B., & Cotič, B. (2021). Urban Strategies Enabling Industrial and Urban Symbiosis: The Case of Slovenia. *Sustainability*, 4616.

Baalamurugan, J., Ganesh Kumar, V., Govindaraju, K., Naveen Prasad, B., Bupesh Raja, V., & Padmapriya, R. (2018). Slag-based nanomaterial in the removal of hexavalent chromium. *Int. J. Nanosci, 17*, 1760013.

Babita, S., Saurabh, U., Abhishek, G., Manoj, Y., Pranjal, B., Ravi, M., & Pankaj, K. (2019). Review paper on partial replacement of cement and aggregates with various industrial waste material and its effect on concrete properties. In *Recycled Waste Materials* (p. 111–117). Berlin/Heidelberg, Germany: Springer.

Baidya, R., Kumar Ghosh, S., & Parlikar, U. (2019). Blast furnace flue dust co-processing in cement kiln–a pilot study. *Waste Manag. Res., 37*, 261–267.

BAMBOO. (H2020-SPIRE-3-2018 Grant Agreement No. 820771, 2018-2022). *Boosting new Approaches for flexibility Management By Optimizing process Off-gas and waste use.* Tratto da http://bambooproject.eu/

Baraldi, L. (217). World production and consumption of ceramic tiles. *Ceram. World Rev.*, 58-70.

BASIS. (European regional Development Fund, 2015-ongoing). *The Birmingham and Solihull Industrial Symbiosis Project.* Tratto da https://www.international-synergies.com/projects/what-is-the-basis-project/

BASSE. (RFSR-CT-2013-00026 01/07/2013-30/06/2016). *Building Active Steel Skin.*

Battelle. (2002). *Toward a sustainable cement industry substudy 8: climate change management and the cement industry.* World Business Council for Sustainable Development .

BEIS. (2017). *Ceramic Sector. Joint Industry - Government Industrial Decarbonisation and Energy Efficiency Roadmap Action Plan.* London: Department for Business, Energy & Industrial Strategy.

BHENEFIT. (2017-2020). *Built heritage, energy and environmental friendly integrated tools for the sustainable management of Historic Built Areas.* Tratto da https://www.interreg-central.eu/Content.Node/BhENEFIT.html

Bianco, L., Porisiensi, S., Baracchini, G., Battigelli, L., & Ceschia, C. (2018). Circular economy in EAF process: how to make it sustainable with zero waste project in Ferriere Nord. *Universal J Manag.*, 190-197.

Biava, G., Zacco, A., Zanoletti, A., Sorrentino, G. P., Capone, C., Princigallo, A., . . . Bontempi, E. (2023). Accelerated Direct Carbonation of Steel Slag and Cement Kiln Dust: An Industrial Symbiosis Strategy Applied in the Bergamo–Brescia Area. *Materials*, 4055.

Bin Abdulwahed, F. (2021). The Hidden Benefits of Energy efficiency: Quantifying the Impact of Non-Energy Benefits When Energy Efficiency Measures Are Implemented in The EU Iron and Steel industry. Master's thesis.

Binnemans, K., Jones, P., Blanpain, B., Van Gerven, T., & Pontikes, Y. (2015). Towards zero-waste valorisation of rare-earth-containing industrial process residues: a critical review. *Journal of Cleaner Production*, 17-38.

BioReSteel. (RFCS; 01/10/2023-31/03/2027). *Valorization of wet biomass residues for sustainable steel production with efficient nutrient recycling.* https://bioresteel.eu/.

Birat, J.-P., Malfa, E., Colla, V., & Thomas, J. (2014). The European Steel Technology Platform’s Strategic Research Agenda Vision For The Sustainable Steel Production 2030s. *Conference: 14th IAEE European Energy Conference on Sustainable Energy Policy and Strategies for Europe.* Rome (Italy).

BLOCK4MAT. (PR-FESR;2021-2027). *BLOckCHain technology for ceramic and construction MATerials supply chain Financial plan:.*

Boom-Cárcamo, E., & Peñabaena-Niebles, R. (2022). Analysis of the Development of Industrial Symbiosis in Emerging and Frontier Market Countries: Barriers and Drivers. *Sustainability*, 4223.

BOOSTEE. (2017-2020). *Boosting Energy Efficiency In Central European Cities Through Smart Energy Management.* Tratto da https://www.interreg-central.eu/Content.Node/BOOSTEE-CE.html

Bouchard, J., Sbarbaro, D., & Desbiens, A. (2018). Plant automation for energy-efficient mineral processing. In *Energy Efficiency in the Minerals Industry* (p. 233-250). Springer, Cham.

Branca, T. A., Colla, V., & Valentini, R. (2009). *Ironmaking & Steelmaking, 36*, 597–602.

Branca, T. A., Colla, V., Fornai, B., Petrucciani, A., Pistelli, M., Faraci, E. L., . . . Schroder, A. J. (2021). Current state of Industrial Symbiosis and Energy Efficiency in the European energy intensive sectors. *Matériaux & Techniques*, 504.

Branca, T. A., Colla, V., Murri, M. M., & Schröder, A. J. (2024). The Impact of the New Technologies and the EU Climate Objectives on the Steel Industry. In *Industry 4.0 and the Road to Sustainable Steelmaking in Europe: Recasting the Future* (p. 53-75). Cham: Springer International Publishing.

Branca, T. A., Vannucci, M., & Colla, V. (2009). A KPI for Local Community Impact of the ULCOS technologies. *Rev. Met., 106*(9), 373-381.

Branca, T., Colla, V., Algermissen, D., Granbom, H., Martini, U., Morillon, A., . . . Rosendahl, S. R.-P. (2020). Reuse and Recycling of By-Products in the Steel Sector: Recent Achievements Paving the Way to Circular Economy and Industrial Symbiosis in Europe. *Metals , 10*, 345.

Branca, T., Fornai, B., Colla, V., Pistocchi, C., & Ragaglini, G. (2019). Application of basic oxygen furnace (bofs) in agriculture: A study on the economic viability and effects on the soil. *Environ. Eng. Manag. J. (Eemj) , 18*, 1231–1244.

Branca, T., Pistocchi, C., Colla, V., Ragaglini, G., Amato, A., Tozzini, C., . . . Romaniello, L. (2014). Investigation of (BOF) converter slag use for agriculture in Europe. *Rev. DeMétallurgie Int. J. Metall, 111*, 155-167.

Brandt, M., Middleton, R., Wheale, G., & Schulting, F. (2011). Energy efficiency in the water industry, a Global Research Project. (p. volume 6, issue2). Water Practice and Technology.

Brunelli, K., & Dabalà, M. (2015). Ultrasound e_ects on zinc recovery from EAF dust by sulfuric acid leaching. *Int. J. Miner. Metall. Mater., 22*, 353–362.

Bunse, K., Vodicka, M., Schönsleben, P., Brülhart, M., & Ernst, F. O. (2011). Integrating energy efficiency performance in production management - gap analysis between industrial needs and scientific literature. *Journal of Cleaner Production, 19*, 667-679.

Bürger, G. (2019). *Reuse of Treated Wastewater in Industrial.* Water and Environmental Engineering Lund University.

BURNER4.0. (RFCS; 01/06/2019 – 30/11/2022). *Development of a new burner concept: Industry 4.0 technologies applied to the best available combustion system for the Steel Industry*.

BurntMillsIndustrialEstate. (Local Government support - Basildon Borough Council, UK, 2016). *Burnt Mills Industrial Estate.* Tratto da https://www.international-synergies.com/projects/transformation-of-burnt-mills-eco-industrial-park-through-industrial-symbiosis

C02OLHEAT. (H2020; 01/06/2021–31/05/2025). *Supercritical CO2 power cycles demonstration in Operational environment Locally valorising industrial Waste Heat*. Tratto da https://cordis.europa.eu/project/id/101022831

C2FUEL. (H2020; 1/06/2019–30/11/2023). *Carbon Captured Fuel and Energy Carriers for an Intensified Steel Off-Gases based Electricity Generation in a Smarter Industrial Ecosystem*. Tratto da https://cordis.europa.eu/project/id/838014

Cantini, A., Leoni, L., De Carlo, F., Salvio, M., Martini, C., & Martini, F. (2021). Technological energy efficiency improvements in cement industries. *Sustainability*, 3810.

CAPTUS. (HORIZON-CL5-2022-D3-02-05; 01/06/2023-31/05/2027). *Demonstrating energy intensive industry-integrated solutions to produce liquid renewable energy carriers from CAPTUred carbon emissionS.* https://cordis.europa.eu/project/id/101118265.

Carbon2Chem project. (s.d.). Tratto da http://www.circulary.eu/project/carbon2chem/

Carbon2Value project. (s.d.). Tratto da https://www.carbon2value.be/en/

Carbon4Minerals. (Horizon.2.4-Digital, Industry and Space; 01/01/2023-31/12/2026). *Transforming CO2 into added-value construction products.* https://cordis.europa.eu/project/id/101091870.

Carbon4PUR. (Horizon 2020-SPIRE-2017, 01/10/2017 – 31/03/2021). *Turning industrial waste gases (mixed CO/CO2 streams) into intermedi-ates for polyurethane plastics for rigid foams/building insulation and coatings*. Tratto da https://www.carbon4pur.eu/

Carlini, M. C. (2019). Application of a circular & green economy model to a ceramic industrial district: An Italian case study. *AIP Conference Proceedings.*

Carns, K. (2005). Bringing Energy Efficiency to the Water & Wastewater Industry: How Do We Get There? *Water Environment Federation's Annual Technical.*

CatASus. (H2020; 01/05/2016-30/04/2023). *Cleave and couple: Fully sustainable catalytic conversion of renewable resources to amines* . Tratto da https://cordis.europa.eu/project/id/678883/reporting

CCS4CER. (PR-FESR;2021-2027). *Carbon capture storage and CO2 mineralization for Ceramic.* https://www.ccs4cer.it/.

Cedefop. (2010). *Skills for green jobs. European synthesis report.* Luxembourg: Publications Office of the European Union.

CEFIC. (2022). *The European Chemical Industry Facts and Figures 2022 .* Tratto da https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/

CELL3DITOR. (s.d.). *H2020, CELL3DITOR.* Tratto da https://www.cell3ditor.eu

Cembureau. (2024). *From Ambition to Deployment - our 2050 roadmap.* Tratto da https://cembureau.eu/library/reports/cembureau-s-net-zero-roadmap/

Centre, E.-E. (s.d.). *Industrial best practices for water management A guide for industry to help reduce your water footprint", .*

CEPS. (2018). Prospects for electric vehicle batteries in a circular economy. *Report N. 2018/05*.

Cerame-Unie. (2012). *Paving the way to 2050, the ceramic industry roadmap*. Tratto da http://cerameunie.eu/: http://cerameunie.eu/topics/cerame-unie-sectors/cerame-unie/ceramic-industry-roadmap-paving-the-way-to-2050/

Cerame-Unie. (2021). *Ceramic Roadmap to 2050.* Tratto da https://www.ceramica.info/cerinfo-content/uploads/2021/12/ceramic-roadmap-to-2050-continuing-our-path-towards-climate-neutrality_LOW.pdf

Cerame-Unie. (2021, June). *Circular Economy & Sustainability.* Tratto da https://cerameunie.eu/media/2884/circular-economy-brochure.pdf

Cerame-Unie. (s.d.). *Cerame-Unie, Facts & Figures*. Tratto da http://cerameunie.eu/ceramic-industry/facts-figures/: http://cerameunie.eu/ceramic-industry/facts-figures/

Ceramica. (2019, January). *The ceramic product and production process and the Circular Economy*. Tratto da Ceramica.info - the official web portal set up by the Italian ceramic industry: https://www.ceramica.info/en/articoli/ceramic-process-circular-economy/

CERAMICS, U. (FP7; 01/02/2012-31/10/2017). *Printed Electroceramics with Ultimate Compositions*. Tratto da https://cordis.europa.eu/project/id/291132/reporting

Cervo, H., Ferrasse, J.-H., Descales, B., & Van Eetvelde, G. (2020). Blueprint: a methodology facilitating data exchanges to enhance the detection of industrial symbiosis opportunities - application to a refinery. *Chemical Engineering Science, 211*. doi:https://doi.org/10.1016/j.ces.2019.115254

CES. (2019). State-of-the-art in reuse and recycling of lithium-ion batteries - A research review. *Circular Energy Storage Report for the Swedish Energy Agency*.

CESAREF. (Horizon.1.2-Marie Skłodowska-Curie Actions (MSCA); 01/10/2022-30/09/2026). *Concerted European action on Sustainable Applications of REFractories.* https://cordis.europa.eu/project/id/101072625.

CESME. (INTERREG EUROPE; 1/04/2016-30/09/2020). *Circular Economy for SMEs.* https://projects2014-2020.interregeurope.eu/cesme/.

CHEERS. (Project reference: 764697 - 01/10/2017 to 30/09/2022). *Chinese-European Emission-Reducing Solutions.*

Chen, H., Yan , Z., Qi zhong Wo, Fei , Y., Jianhua, W., Yan, G., & Qinyao, Z. (2015). Modi-fied PCC used in papermaking processes. *BioResources*, 5125-5139.

Chertow, M. (2000). Industrial symbiosis: literature and taxonomy. *Annu. Rev. Energy Environ., 25*, 313-337.

Chertow, M. L. (2005). Quantifying Economic and Environmental Benefits of Co-Located Firms. *Environ. Sci. Technol. 39*, 6535–6541.

CHINA, L. C. (Wuhan's Strategic Plan for Integrated Urban Development, 2017). *CHINA, Low Carbon Strategy for Hubei Province.* Tratto da https://www.international-synergies.com/projects/integration-of-industrial-symbiosis-in-wuhans-strategic-urban-development-plan/

Chiriac, S., Puscasu, M.-E., Tudor, I. A., Matei, A. C., Cursaru, L. M., & Piticescu, R. R. (2022). Development of 3D ZnO-CNT Support Structures Impregnated with Inorganic Salts. *Membranes*, 588.

Chopra, S. K. (2014). Understanding resilience in industrial symbiosis networks: Insights from network analysis. *J. Environ. Manage. 141*, 86–94.

Christos Agrafiotis, T. T. (2001). Energy saving technologies in the European ceramic sector: a systematic review . *Applied Thermal Engineering*, 1231-1249.

CHROMIC. (Horizon 2020 – GA No. 730471; 1/11/2017-31/10/2020). *Efficient mineral processing and Hydrometallurgical RecOvery of by-product Metals from low-grade metal containing secondary raw materials () .*

CICERONE. (H2020, 2018-2020). *Closing the loop on circular economy research & innovation.* Tratto da http://cicerone-h2020.eu/

CIRCOTRONIC. (INTERREG CENTRAL; 03/2023-02/2026). *Transnational Network of Circular Labs for EEE.* https://www.interreg-central.eu/projects/circotronic/.

CIRCULARCARBON. (2021- ongoing). *Valencian Institute of Business Competitiveness (IVACE) through the FEDER Regional Development Funds*. Tratto da https://www.itc.uji.es/en/no-te-pierdas-elultimo-video-del-proyecto-circularcarbon/

CircularSociety, I. (EIT Raw Materials, 1 January 2020-31 December 2023). *European Higher Technician for Regenerative Circular Society.* Tratto da https://www.aster.it/en/ifts-circular-society-eu-higher-technician-regenerative-circular-society

CLEANTECHBLOCK2. (H2020-EU.3.5. H2020-EU.2.3.1; H2020-SMEINST-2-2016-2017 - Grant agreement ID: 766614; 2017-2019). *CLEANTECHBLOCK2*. Tratto da https://cordis.europa.eu/project/id/766614

CO2ncrEAT. (Innovation Fund; 2023-2033). *Industrialisation of the mineralization technology for building blocks using double circularity of lime process CO2 emissions.* https://eula.eu/wp-content/uploads/2023/09/EuLA-Innovation-Booklet-3.0-EN-WEB.pdf.

CoACH. (H2020; 01/01/2015-31/12/2018). *Advanced glasses, Composites And Ceramics for High growth Industries*. Tratto da https://cordis.europa.eu/project/id/642557/reporting

COCOP. (H2020 Ct No 723661; 2016-2020). *Coordinating Optimisation of COmplex Industrial Processes.*

Colla, V., Branca, T. A., Pietruck, R., Wolfelschneider, S., Morillon, A., Algermissen, D., . . . Snaet, D. (2023). Future research and developments on reuse and recycling of steelmaking by-products. *Metals*, 676.

Colla, V., Matino, I., Branca, T. A., Fornai, B., Romaniello, L., & Rosito, F. (2017). Efficient Use of Water Resources in the Steel Industry. *Water, 9*(11), 874.

Colla, V., Matino, I., Cirilli, F., Jochler, G., Kleimt, B., Rosemann, H., . . . De Miranda, U. (2016). Improving energy and resource efficiency of electric steelmaking through simulation tools and process data analyses. *Materiaux&Tecniques, 104*(602).

Colla, V., Matino, I., Dettori, S., Cateni, S., & Matino, R. (2019). Reservoir computing approaches applied to energy management in industry. *Communications in Computer and Information Science,*, 1000: 66-79.

Colla, V., Matino, I., Dettori, S., Petrucciani, A., Zaccara , A., Weber, V., . . . Romaniello, L. (2018, December). Assessing the efficiency of the off-gas network management in integrated steelwork. *Matériaux & Techniques, 106*(1).

COLUMBUS. (Strategic Forum for Important Projects of Common European Interest (IPCEI)–via EU Innovation Fund; 2022–2025). *Power to Methane.* https://eula.eu/wp-content/uploads/2023/09/EuLA-Innovation-Booklet-3.0-EN-WEB.pdf.

COM©TRANS. (M-ERA.NET 2020; 01/06/2021–31/12/2023). *Composites Based on Compositionally Complex Alloys for Transportation Industry*. Tratto da www.imnr.ro/comptrans

Commission, E. (2011). *Roadmap to a Resource Efficient Europe COM (2011) 571 Final.* Brussels: European Commission.

Commission, E. (2015). *Closing the Loop—An EU Action Plan for the Circular Economy - COM(2015) 614 Final .* Brusselles: European Commission.

Commission, E. (2018). *Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste.* Tratto da EUR-Lex: http://data.europa.eu/eli/dir/2018/851/oj

Commission, E. (2018a). *Measuring Progress towards Circular Economy in the European Union e Key Indicators for a Monitoring Framework 16.1.2018. SWD(2018) 17 final.* Brussells: European Commission.

Commission, E. (2018b). *Proposal for a Decision of the European Parliament and of the Council on Establishing the Specific Programme Implementing Horizon Europe e the Framework Programme for Research and Innovation .* Brussells: European Commission.

Commission, E. (2020, March 11). *Changing how we produce and consume: New Circular Economy Action Plan shows the way to a climate-neutral, competitive economy of empowered consumers.* Tratto da https://ec.europa.eu/commission/presscorner/detail/en/ip_20_420

Commission, E. (2020). *Circular Economy Action Plan. For a cleaner and more competitive Europe.* Retrieved from https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf.

Commission, E. (s.d.). *Directive 2008/98/EC of the European Parliament and of the Council of 19 Novem-ber 2008 on Waste and Repealing Certain Directives.* Tratto da (Waste Framework Directive, R1 Formula in Footnote of Attachment II).: Available online: http://eur-lex.Europa.Eu/lexuriserv

Commission, E. (November 09, 2017). *A Roadmap for Moving to a Competitive Low Carbon Economy in 2050 .* Brussels.

COMSYN. (Project reference: 727476; 01/05/2017 to 30/04/2021). *Compact Gasification and Synthesis process for Transport Fuels.*

CONNECT, 2. (Interreg Vlaanderen-Nederland; 2019-2020). *2B CONNECT*. Tratto da https://www.2b-connect.be/

CONVERGE. (Project reference: 818135, 01/11/2018 to 30/04/2022). *CarbON Valorisation in Energy-efficient Green fuels.*

Cooperation1. (s.d.). *Cooperation fostering industrial symbiosis: market potential, good practice and policy actions, Internal Market, Industry, Entrepreneurship and SMEs.* Tratto da https://op.europa.eu/en/publication-detail/-/publication/174996c9-3947-11e8-b5fe-01aa75ed71a1/language-en

Cooperation2. (CLIMATE KIC, 2017-2018). *Cooperation Fostering Industrial Symbiosis.* Tratto da https://publications.europa.eu/en/publication-detail/-/publication/174996c9-3947-11e8-b5fe-01aa75ed71a1/language-en

COPRO. (H2020, Grant Agreement No 723575, 2016-2020). *Improved energy and resource efficiency by better coordination of production in the process industries.*

CORALIS. (H2020, under the agreement n. 958337; 2020-2023). *Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis.* https://www.coralis-h2020.eu/.

CORESYM. (2017, December). *CarbOn-monoxide RE-use through industrial SYMbiosis between steel and chemical industries*. Tratto da https://www.metabolic.nl/publications/coresym-carbon-monoxide-re-use-through-industrial-symbiosis/

CORNERSTONE. (Horizon.2.4-Digital, Industry and Space; 01/01/2024-31/12/2027). *Combined technologies for water, energy and solute recovery from industrial process streams.* https://cordis.europa.eu/project/id/101138504.

COSME, E. A.-s. (2020). *Blueprint For Sec-toral Cooperation On Skills: Towards An Eu Strategy Addressing The Skills Needs Of The Steel Sector, European vision on steel-related skills and supporting actions to solve the skills gap today and tomorrow in Europe.* Brusselles: Executive Agency for Small and Medium-sized Enterprises (EASME) COSME, Blueprint For Sec-toral Cooperation On Skills: Towards An Eu Strategy Addressing The Skills Needs Of The Steel Sector, European vision on steel-related skills and supporting actions to.

Costa, I., & Ferrao, P. (2010). A case study of industrial symbiosis development using a middle-out approach. *Journal of Cleaner Production, 18*(10-11).

Council of the European Union. (2007). *European Council 8/9 March 2007.* Brussels: Council of the European UniCouncil of the European Union.

Courtois, M. (2017). *Social strategies for FISSAC: Strategies for social engagement and ac-ceptance.*

CRAM. (2016-2019). *CRAM - TOWARDS A RAW MATERIALS STRATEGY FOR THE EUROPEAN CERAMIC IN-DUSTRY, Regional project.* Tratto da https://ec.europa.eu/growth/content/towards-raw-materials-strategy-european-ceramic-industry_en

CSM. (Funding National Finnish Funding Agency for Technology & Innovation (TEKES); 2011–2016). *Carbon Storage by Mineralisation.* https://eula.eu/wp-content/uploads/2023/09/EuLA-Innovation-Booklet-3.0-EN-WEB.pdf.

CUMERI. (HORIZON-CL4-2022-RESILIENCE-01; 01/12/2022-30/11/2025). *Customised membranes for green and resilient industries.* https://cordis.europa.eu/project/id/101091812.

Curry, J., Mansel, J., & Graeme, J. (2014). Mine operating costs and the potential impacts of energy and grinding. *Minerals Engineering*, 70-80.

Davydenko, A., Karasev, A., Glaser, B., & Jönsson, P. (2019). Direct reduction of Fe, Ni and Cr from oxides of waste products used in briquettes for slag foaming in EAF. *Materials, 12*, 3434.

de Bruyn, S., Jongsma, C., Kampman, B., G¨orlach, B., & Thie, J.-E. (2020). *Energy-intensive Industries – Challenges and Opportunities in Energy Transition, Study for the Committee on Industry, Research and Energy (ITRE). Policy Department for Economic, Scientific and Quality of Life Policies.* Tratto da https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_190414_Energy_Intensive_Industries_DEF.pdf

De Groen, F. (2018). The interaction between an industry revitalised through Industrial Symbiosis and its local workforce: A socially aware exploratory agent-based model of the sugar industry in Norte Fluminense, Brazil.

DELTA. (H2020 GA No 773960; 2018-2021). *Future tamper-proof Demand rEsponse framework through seLf-configured, self-opTimized and collAborative virtual distributed energy nodes.*

Desha, C., & Hargroves, K. (2014). *Higher Education and Sustainable Development. A Model for Curriculum Renewal.* New York, NY, USA: Routledge.

Dessart, F. J. (2017). *Non-ferrous Metals Manufacturing: Vision for 2050 and Actions Needed.* Joint Research Centre (JRC) report, EUR 28538 EN.

DESTINY. (Horizon 2020 - SPIRE Grant agreement No 820783; 2018-2022). *Development of an Efficient Microwave System for Material Transformation In Energy Intensive Processes for an Improved Yield*. Tratto da https://www.destinyh2020andbeyond.eu/

Dettori, S., Matino, I., Colla, V., & Speets, R. (2020). Deep Echo State Networks in Industrial Applications. In I. L. Maglogiannis I., *Artificial Intelligence Applications and Innovations* (Vol. 584, pp. 53-63). Springer, Cham. doi:https://doi.org/10.1007/978-3-030-49186-4_5

Dettori, S., Matino, I., Colla, V., & Speets, R. (2022). A Deep Learning-based approach for forecas-ting off-gas production and consumption in the blast furnace. *Neural Computing and Applications*, 911-923.

Detwiler, R. T. (2003). The Use of Limestone in Portland Cement : A State-Of-The-Art Review.

Devasahayam, S. (2019). Opportunities for simultaneous energy/materials conversion of carbon dioxide and plastics in met-allurgical processes. *Sustain. Mater. Technol. , 22*, e00119.

Di Sante, L., Cirilli, F., & Angelucci, N. (2013). EAF slag: A product no longer a problem. *Iron and Steel Technology*, 257-265.

DOC3D. (2018-tbc). *Horizon 2020 under the Marie Skłodowska-Curie grant agreement No 764935, DOC3D PRINTING.* Tratto da http://www.doc-3d-printing.eu/en/about-the-project/project-overview.html

Draxler, M., Schenk, J., Bürgler, T., & Sormann, A. (2020). The Steel Industry in the European Union on the Crossroad to Carbon Lean Production—Status, Initiatives and Challenges. *BHM Berg- und Hüttenmännische Monatshefte*, 221-226.

Draxler, M., Sormann, A., Kempken, T., BFI, T., Pierret, J., Di Donato, A., & Wang, C. (2021). *Technology Assessment and Roadmapping (Deliverable 1.2).* Tratto da https://www.estep.eu/assets/Uploads/D1.2-Technology-Assessment-and-Roadmapping.pdf

DREAM. (2016-2019). *H2020-SPIRE2016, DREAM -Design for Resource and Energy efficiency in cerAMic kilns.* Tratto da http://cordis.europa.eu/project/rcn/205615_en.html https://www.spire2030.eu/dream.

DRYficiency. (H2020-EE-2016-PPP (SPIRE); 01/09/2016-31/08/2020). *Waste Heat Recovery in Industrial Drying Processes*. Tratto da https://cordis.europa.eu/project/id/723576

Dust2Value. (Horizon-CL4-2023-TWIN-TRANSITION-01; 01/01/2024-31/12/2026). *Pioneering Sustainable Recovery in Steelmaking: Hydrogen-Based Technology for Byproduct Management.* https://cordis.europa.eu/project/id/101138742.

DYNERGYSTEEL. (RFSR-CT-2014-00029; 01/07/2014-31/12/2017). *Integrated dynamic energy management for steel production.*

E4WATER. (FP7; 01/05/2012-30/04/2016). *Economically and Ecologically Efficient Water Management in the European Chemi-cal Industry*. Tratto da https://cordis.europa.eu/project/id/280756/reporting

EC. (2020). *ntelligent-energy-europe*. Tratto da ec.europa.eu: https://ec.europa.eu/easme/en/section/energy/intelligent-energy-europe

ECEG, & industriAll Europe. (2023). *Joint Statement on the impact of the energy crisis on the EU chemical industry.* Tratto da https://www.eceg.org/_files/ugd/977a5c_d8615a48cb134b1685c384377a3e21b5.pdf

ECO/08/239051/SI2.534294. (2009-2012). *"Sensor-sorting Automated Technology for advanced Recovery of Non-ferrous metals".* http://www.saturn.rwth-aachen.de/index.php.html .

ECO-binder. (H2020; 01/01/2015-31/12/2018). *Development of insulating concrete systems based on novel low CO2 binders*. Tratto da https://cordis.europa.eu/project/id/637138

ECOCARB. (RFCR-CT-2008-00007; 31/07/008-31/12/2011). *Reduction of emissions and energy utilisation of coke oven underfiring heating systems through advanced diagnostics and control.*

ECOFILLINK. (European Regional Development Fund; 2020-2021). Retrieved from https://www.itc.uji.es/en/the-ecofillink-project-will-help-reduce-the-environmental-impact-generated-by-ink-jet-ink-containers/

E-CO-LadleBrick. (2019 –2022). *Ecological and Economical waste management of the ladle refractory bricks by imple-menting circular economy criteria.*

ECONOMICK. (2016-2019). *LIFE15, CCM/IT/000104, ECONOMICK.* Tratto da www.economick.eu

ECOSISTER. (National Recovery Fund (PNRR); 2022-2025). *Ecosystem for sustainable transition in Emilia-Romagna*.

ECOSLAG. (RFCS-CT-2018-800762; 1/06/2018-30/11/2021). *Eco-friendly steelmaking slag solidification with energy recovery to produce a high-quality slag product for a sustainable recycling.*

ECP. (PRR; 2022-2025). *Ecocerâmica e Cristalaria de Portugal.* https://agendaecp.pt/en.

EEBIS. (RFSR-CT-2003-00017 01/09/2003-31/08/2006). *Energy efficient buildings through innovative systems in steel.*

EGGSHELLENCE, L. (Life+; 2020-2024). *A potential raw material for ceramic wall tiles*. Tratto da https://www.lifeeggshellence.eu/

EIPPCB, I. P. (2007). *Reference Document on Best Available Techniques (BATs) in the Ceramic Manufacturing Industry.* Sevilla: European Commission, Directorate-general JRC, Joint Research Centre. Institute for Prospective Technological Studies .

EIRES. (RFCS-CT-2013-00030; 01/07/2013-31/12/2016). *Environmental impact evaluation and effective management of resources in the EAF steelmaking.*

El-Azim, H., Seleman, M.-S., & Saad, E. (2019). Applicability of water-spray electric arc furnace steel slag for removal of cd and mn ions from aqueous solutions and industrial wastewaters. J. Environ. Chem. Eng. 2019, 7, 102915. *J. Environ. Chem. Eng. , 7*, 102915.

ENACT. (2014-2016). *Energy Auditors Competencies, Training and Profiles.* Tratto da http://www.enactplus.eu/

ENCOP. (RFSR-CT-2009-00032 01/07/2009-31/12/2013). *Development of tools for reduction of energy demand and CO2-emissions within the iron and steel industry based on energy register, CO2 monitoring and waste heat power generation.*

ENERGEIA. (Interreg Med Programme, 2011-2013). *Energy Enterprise Generation in the Med Area.* Tratto da http://ftz.org.mt/energeiamed/the-energeia-project

ENERGYDB. (RFSR-CT-2013-00027 01/07/2007-31/12/2010). *Application of a factory wide and product related energy database for energy reduction.*

ENERHIGH. ((Structural funds); 09/09/2016-2019,). *Innovative Methods for Enhancing High Temperature Thermal Energy Storage Properties of Phase Change Materials*. Tratto da www.imnr.ro/enerhigh

EnerMIND. (G.A. 899345; 01/07/2020-31/12/2023). *Energy Management in the Era of Industry 4.0.*

(SMEs, Manufacturing Industry, Entrepreneurs, R&D Centers, Investors, Public Institutions; 21/07/2022-20/07/2024). *Enhancing the Rare Earth Elements (REEs) Research and Innovation Capacity of Turkey .* https://ab.gov.tr/enhancing-the-rare-earth-elements-rees-research-and-innovation-capacity-of-turkey_53434_en.html.

ENVIP. (2013-2015). *LIFE12 ENV/ES/000598, ENVIP - NEW ENVIRONMENTALLY FRIENDLY FORMING TECH-NIQUE OF CERAMIC SANITARYWARE BY ISOSTATIC PRESSING.*

Environment, T. S. (Innovate UK, June 2014-November 2014). *Technology Strategy Board Environmental Data: Novel materials for the Built Environment.* Tratto da https://www.international-synergies.com/projects/alternative-raw-materials/

Environment, T. S. (Innovate UK, June 2014-November 2014). *Technology Strategy Board Environmental Data: Novel materials for the Built Environment UK.* Tratto da https://www.international-synergies.com/projects/alternative-raw-materials/

EPOS. (Horizon 2020, 2015-2019). *Enhanced energy and resource Efficiency and Performance in process industry Operations via onsite and cross-sectorial Symbiosis.* Tratto da https://www.spire2030.eu/epos

EPOSS. (RFSR-CT-2007-00006 ; 1/07/2007-31/12/2010). *Energy and productivity optimised EAF stainless steel making by adjusted slag foaming and chemical energy supply .*

EROS. (Ministry of Science, Innovation and Universities – Spain; 2020-2022). *Circular Economy in composites: from the wind and aeronautical sector to the ceramic and plastic industry*. Tratto da https://www.itc.uji.es/en/el-itccolabora-en-eros-economia-circularpara-incorporar-residuos-de-otrossectores-a-la-ceramica-y-eltransporte/

ETHICS. (RFSR-CT-2008-00038 01/07/2008-30/06/2011). *Energy and thermal improvements for construction in steel.*

EUCERMAT. (2015-2018). *EUCERMAT: EUROPEAN CERAMIC MATERIALS, Erasmus+ program.* Tratto da http://www.eucermat.eu/eucermat/

EUROFER. (2019). *Low Carbon Roadmap - Pathways to a CO2-neutral European Steel Industry.* Tratto da https://www.eurofer.eu/assets/Uploads/EUROFER-Low-Carbon-Roadmap-Pathways-to-a-CO2-neutral-European-Steel-Industry.pdf

EUROFER. (2020). *2020 European Steel in Figures. European Steel Association.*

Eurometaux, 2. (2018). *Eurometaux's proposed measures to ensure an effective EU circular economy, Position paper, https://copperalliance.eu/uploads/2018/01/2015-03-26-em-circular-economy-position-paper-2.pdf.*

Europe, C. (2021). *The European Pact for Sustainable Industry 2030.* Tratto da https://www.csreurope.org/the-european-pact-for-sustainable-industry

European Commission. (2010). *Communication No. 2020, 2010. Europe 2020—A Strategy for Smart, Sustainable and Inclusive Growth; (COM No. 2020, 2010); .* Brussels: Commission of European Communities.

European Commission. (2011). *Roadmap for Moving to a Low-Carbon Economy in 2050.* Tratto da https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0112:FIN:EN:PDF

European Commission. (2012). *Energy roadmap 2050.* Tratto da https://ec.europa.eu/energy/sites/ener/files/documents/2012_energy_roadmap_2050_en_0.pdf

European Commission. (2014). *Energy Efficiency and CO2 Reduction in the Iron and Steel Industry (SETIS).* Brussels.: European Commission.

European Commission. (2015). *A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy; COM/2015/080 Final, February 25.* Brussels: European Commission.

European Commission. (2019). *National energy and climate plans (NECPs).* Tratto da https://ec.europa.eu/energy/topics/energy-strategy/national-energy-climate-plans_en

European Commission. (2020a). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A New Circular Economy Action Plan for a Cleaner and More Competitive Europe, COM/2020/98 final.* Brussels: European Commission.

European Commission, 2. (2010). *Report on Critical Raw Materials for the EU. Report of the Ad hoc Working Group on defining critical raw materials. .*

European Commission, 2. (2014). *Report on Critical Raw Materials for the EU. Report of the Ad hoc Working Group on defining critical raw materials.*

European Commission. (2010). *Communication No. 2020, 2010. Europe 2020—A Strategy for Smart, Sustainable and Inclusive Growth; (COM No. 2020, 2010).* Brussels: Commission of European Communities.

European Parliament . (2020b). *Regulation of the European Parliament and of the Council Establishing the Framework for Achieving Climate Neutrality and Amending Regulation (EU) 2018/1999 (European Climate Law) (Proposal No. COM(2020) 80 Final).* Brussels.

European Parliament and Council. (2012). *Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, Amending Directives 2009/125/EC and 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC Text with EEA Relevance.* Tratto da https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012L0027

European Parliament and Council. (2012). *Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, Amending Directives 2009/125/EC and 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC Text with EEA Relevance.* Tratto da https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX: 32012L0027

European Union. (2016, August). *The Macroeconomic and Other Benefits of Energy Efficiency.* Tratto da https://ec.europa.eu/energy/sites/ener/files/documents/final_report_v4_final.pdf

European, A. (2023, November). *GLOBAL ARRANGEMENT ON SUSTAINABLE STEEL AND ALUMINIUM Together for Climate-neutrality. Together for restoring market-based trade.* Tratto da https://european-aluminium.eu/wp-content/uploads/2023/11/Global-Arrangement-PP-update_Nov-2023.pdf

Eurostat. Air Emiss. Acc. NACE. (s.d.). Tratto da https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_a c_ainah_r2&lang=en, 8.26.20.

Fareri, S., Apreda, R., Mulas, V., & Alonso, R. (2023). The worker profiler: Assessing the digital skill gaps for enhancing energy efficiency in manufacturing. *Technological Forecasting and Social Change*, 122844.

Fasolini, S., & Martino, M. R. (s.d.). *Fasolini, S.; Martino, M. .* Tratto il giorno June 2020 da Recovery of Spent Refractories: How to Do It and Using Them as Secondary Raw Materials for Refractory Applications: http://www.indmin.com/events/download.ashx/document/speaker/8915/a0ID000000ZwxAQMAZ/Presentation

FAST-SMART. (H2020; 01/04/2020–31/03/2024). *FAST and Nano-Enabled SMART Materials, Structures and Systems for Energy Harvesting*. Tratto da www.fast-smart.org.

Feiz, R. A. (2013). Improving the CO2 performance of cement, part I: Utilizing life-cycle assessment and key performance indi-cators to assess development within the cement industry [under re. *Journal of Cleaner Production*.

FERTILIFE. (2015-2018). *LIFE14 CCM/ES/000311, FERTILIFE – AGRICULTURAL CARBONIC FERTILIZATION WITH CERAMIC INDUSTRY GEI EMISSIONS.* Tratto da https://www.fertilife-project.eu/

Fick, G., Mirgaux, O., Neau, P., & Patisson, F. (2014). Using biomass for pig iron production: A technical, environmental and eco-nomical assessment. *Waste Biomass Valor. , 5*, 43-55.

FINES2EAF. (RFCS-CT-2017-754197; 01/07/2017-31/12/2020). *Cement-free brick production technology for the use of primary and second-ary raw material fines in EAF steelmaking.*

Finnerty, N., Sterling, R., Coakley, D., Contreras, S., Coffey, R., & Keane, M. (2017). Development of a glob-al energy management system for non-energy intensive multi-site industrial organisations: A methodology. *Energy*, 16–31.

FIRECE. (Interreg Central EU, 2017-2020). *Innovative Financial Instruments for industry low carbon energy transition in Central Europe.* Tratto da https://www.interreg-central.eu/Content.Node/FIRECE.html

Fisher, L., & Barron, A. (2019). The recycling and reuse of steelmaking slags—A review. Resour. Conserv. Recycl. 2019, 146, 244–255. *Resour. Conserv. Recycl. , 146*, 244–255.

FISS. (International development – Finland, 2013-ongoing). *The Finnish Industrial Symbiosis System, International development .* Tratto da https://www.motiva.fi/yritykset/verkostot/teolliset_symbioosit_fiss

FISSAC. (H2020 WASTE 2014; 1/09/2015 – 29/02/2020). *Fostering industrial symbiosis for a sustainable resource intensive industry across the extended construction value chain ().* https://cordis.europa.eu/project/id/642154.

FLEXCHARGE. (RFSR-CT-2007-00008 01/07/2007-31/12/2010). *"Cost and energy effective management of EAF with flexible charge material mix".*

FLEXIndustries. (Horizon.2.4-Digital, Industry and Space; 01/06/2022-31/05/2026). *Digitally-enabled FLEXible Industries for reliable energy grids under high penetration of Variable Renewable Energy Sources (VRES).* https://cordis.europa.eu/project/id/101058453.

FLEXINJECT. (RFSR-CT-2008-00001; 1/07/2008-31/12/2011). *Flexible injection of alternative carbon material into the blast furnace ().*

FORGE. (H2020; 2020-2024). *Development of novel and cost-effective coatings for high-energy processing applications*. Tratto da https://www.forge-project.eu/

FORTURE. (LIFE16 ENV/IT/000307; 2017-2021). *Force of the Future.* https://www.forture-life.eu/.

FP7-POLFREE. (FP7-Environment; Grant Agreement No 308371, 2012-2016). *Policies Options for a Resource Efficient Economy.* Tratto da https://www.ucl.ac.uk/polfree

Fraccascia, L., Yazdanpanah, V., van Capelleveen, G., & Yazan, D. M. (2021). Energy-based industrial symbiosis: A literature review for circular energy transition. *Environment, Development and Sustainability*, 4791-4825.

FresMe project. (s.d.). Tratto da http://www.fresme.eu/

Fullana Puig, L. (2019). *Comparative study of Industrial Symbiosis in Italy and Spain. BS thesis.* Universitat Politècnica de Catalunya.

FUTURING. (H2020, Grant Agreement N. 723633, 2016-2018). *Futuring European Industry.*

Gabris, M., & Ping, J. (2021). Carbon nanomaterial-based nanogenerators for harvesting energy from environment. *Nano Energy*, 106494.

GASNET. (RFSR-CT-2015-00029 01/07/2015-31/12/2018). *Optimization of the management of the process gases network within the integrated steelworks.*

George, E. R. (2019). High-entropy alloys . *Nature reviews materials*, 515-534.

German Federal Ministry of Environment. (2012-2014). Lithorec Process. *German Federal Mministry of the environment*.

Ghiță, A.-N., Slobozeanu, A. E., Licu, L., Ciobota, C. F., Sobetkii, A., Vasile, B. S., . . . Piticescu, R. R. (2024). Hydrothermal synthesis of zirconia doped with naturally mixed rare earths oxides and their electrochemical properties for possible applications in solid oxide fuel cells. *Manufacturing Rev.*, 1.

Ghosh et al. (2015). *“Waste Printed Circuit Boards recycling: an extensive assessment of current status”.* Journal of Cleaner Production, 94, 5-19.

Goldman, C. A. (2010). *Energy Efficiency Services Sector: Workforce Education and Training Needs.* Berkeley, CA (United States): Lawrence Berkeley National Lab.(LBNL).

Gomes, H., Funari, V., Mayes, W., Rogerson, M., & Prior, T. (2018). Recovery of Al, Cr and V from steel slag by bioleaching: Batch and column experiments. *J. Environ. Manag, 222*, 30–36.

Gonzalez-Olmos, R., Anfruns, A., Aguirre, N., Masaguer, V., Concheso, A., & Montes-Morán, M. (2018). Use of by-products from integrated steel plants as catalysts for the removal of trichloroethylene from groundwater. *Chemosphere, 213*, 164–171.

Goti, A., Akyazi, T., Loroño, A., Oyarbide, A., Alberdi , E., & Ukar, O. (2023). Identifying the Future Skills Requirements of the Job Profiles Related to Sustainability in the Engineering Sector.". *Journal of Positive Psychology and Wellbeing*, 292-309.

Grant Agreement ID: 32493, F.-S. (2006-2008). *“Innovative Separaction Method Non Ferrous Metal Waste from Electric and Electronic Equipment WEEE based on Multi and Hyper spectral Identification”.* https://cordis.europa.eu/project/id/32493/reporting/it .

Grant agreement ID: 508212, 2.-2. F.-S. (s.d.). “Liquid crystal display re-use and recy-cling”.

Grant Agreement ID: 603564, 2.-2. F.-E. (s.d.). “Recovery of Rare Earth Elements from magnetic waste in the WEEE recycling industry and tailings from the iron ore industry”. *” https://cordis.europa.eu/project/id/603564/reporting/fr*.

Grant agreement ID: 603676, F.-E. (2014-2016). *"Selective recovery of non-ferrous metal automotive shredder by combined electromagnetic tensor spectroscopy and laser-induced plasma spectroscopy".* https://cordis.europa.eu/project/id/603676.

Grant agreement ID: 604140, F.-N. 2.-2. (s.d.). Innovative tools, methods and indicators for optimizing the resource efficiency in process industry. *https://cordis.europa.eu/project/id/604140*.

Grant agreement ID: 636816, H.-E. 2.-2. (s.d.). Metrics for Sustainability Assessment in European Process Industries. *https://cordis.europa.eu/project/id/636816*.

Grant agreement ID: 641972, 2.-2. H.-E. (s.d.). "Implementation of a CirculAr economy Based on Recycled, reused and recovered Indium, Silicon and Silver mate-rials for photovoltaic and other applications". *https://www.spire2030.eu/cabriss/*.

Grant Agreement ID: 641999, 2.-2. H.-E. (s.d.). "Prospecting Second-ary Raw Materials in the Urban Mine and mining wastes". *http://www.prosumproject.eu/*.

Grant Agreement ID: 690088, H.-E. (2016-2020). *"Metal Recovery from Low Grade Ores and Wastes".* https://metgrowplus.eu/.

Grant agreement ID: 694078, H.-E. (2016-2021). *"Solvometallurgy for critical metals".* https://solcrimet.eu/.

Grant agreement ID: 694638, H.-E. 2.-2. (s.d.). Applying energy efficient measures for metal and metalworking SMEs and industry . *https://cordis.europa.eu/project/id/694638/it*.

Grant Agreement ID: 721185, H. (2016-2020). *"European Training Network for Resource Recovery Through Enhanced Landfill Mining" .* http://new-mine.eu/project/.

Grant agreement ID: 768772, H.-E. 2.-2. (s.d.). Heat pipe technology for thermal energy recovery in industrial applications . *https://cordis.europa.eu/project/id/768772* .

Grant agreement ID: 776469, 2.-2. H. (2014-2020). *"Removing the waste streams from the primary Aluminium production and other metal sectors in Europe".* https://www.removal-project.com/.

Grant agreement ID: 776517, 2.-2. H.-E. (s.d.). "Optimising quality of information in RAw MAterials data collection across Europe". *https://orama-h2020.eu/*.

Grant agreement ID: 776714, 2.-2. H.-E. (s.d.). Activating Circular Services in the Electrical and Electronic Sector. *https://c-serveesproject.eu/*.

Grant agreement ID: 869815, H.-E. 2.-2. (s.d.). Optimization and performance improving in metal industry by digital technologies . *https://cordis.europa.eu/project/id/869815*.

GreenBricks. (AT: FFG/NEFI(New Energy For Industry);01/10/2022-03/09/2025). *The Carbon Neutral Brick Factory (tunnel kiln driven by green electricity and a new carbon neutral clay blend formulation).* https://www.nefi.at/en/project/GreenBricks.

GreenEAF. (RFSR-CT-2009-00004; 01/07/2009 - 30/06/2012). *Sustainable electric steel production.*

GREENEAF2. (RFSP-CT-2014-00003; 1/07/2014 - 30/06/2016). *Biochar for a sustainable EAF steel production.*

GreenHeatEAF. (Horizon.2.4-Digital, Industry and Space; 01/01/2023-30/06/2026). *Gradual integration of REnewable non-fossil ENergy sources and modular HEATing technologies in EAF for progressive CO2 decrease.* https://cordis.europa.eu/project/id/101092328.

GREENSTAR. (Lifelong Learning Programme - Leonardo da Vinci, 2013-2015). *Green Skills along the Value Chain of the Automotive Suppliers Industry.* Tratto da http://www.greenskills-project.eu/

GRESMALT. (s.d.). *G3NIUS-CARBON FOOTPRINT OF PRODUCTS (CFP).* Tratto da https://www.frassinoroceramiche.it/wp-content/uploads/2024/02/CFP_G3NIUS_12_01_2024_VERSIONE.pdf

GRESMALT. (s.d.). *G3NIUS-ENVIRONMENTAL PRODUCT DECLARATION.* Tratto da https://www.frassinoroceramiche.it/wp-content/uploads/2024/01/EPD_G3NIUS.pdf

Grillo, F., Coleti, J., Espinosa, D., Oliveira, J., & Tenório, J. Z.–3. (2014). Zn and Fe recovery from electric arc furnace dusts. *Mater. Trans., 55*, 351–356.

GT-VET. (Lifelong Learning Programme - Leonardo da Vinci, 2011-2012). *Greening technical Vocational Education and Training in the Steel Industry.* Tratto da https://www.estep.eu/estep-at-a-glance/involvement/gt-vet; https://ec.europa.eu/programmes/erasmus-plus/video/skills-alliances_en

Guo, W. T. (2017). Industrial Energy Training and Certification. *Plant Engineering* .

Gutierrez, A., Miró, L., Gil, A., Rodríguez-Aseguinolaza, J., Barreneche, C., Calvet, N., . . . Ushak, S. A.-p. (2016). Advances in the valorization of waste and by-product materials as thermal energy storage (TES) materials. *Renew. Sustain. Energy Rev., 59*, 763–783.

Gwon, H., Khan, M., Alam, M., Das, S., & Kim, P. (2018). Environmental risk assessment of steelmaking slags and the potential use of ld slag in mitigating methane emissions and the grain arsenic level in rice (oryza sativa l). *J. Hazard. Mater., 353*, 236–243.

H2Glass. (Horizon Europe; 2023-2026). *advancing Hydrogen (H2) technologies and smart production systems TO decarbonise the GLass and Aluminium SectorS.* https://h2-glass.eu/.

H2PlasmaRed. (Horizon-CL4-2023-Twin-Transition-01; 01/01/2024-31/12/2027). *Hydrogen Plasma Reduction for Steelmaking and Circular Economy.* https://cordis.europa.eu/project/id/101138228.

H2STEEL. (Horizon.3.1-The European Innovation Council (EIC); 01/10/2022-30/09/2025). *Green H2 and circular bio-coal from biowaste for cost-competitive sustainable Steel.* https://cordis.europa.eu/project/id/101070741.

Hadera, H., Ekström, J., Sand, G., & Mäntysaari, J. (2019). Integration of production scheduling and energy-cost optimization using Mean Value Cross Decomposition. *Computers and Chemical Engineering, 129, 2019, 129*.

HARMONI. (H2020-IND-CE-2016-2017/H2020-SPIRE-2017, 2017-2019). *Harmonised assessment of regulatory bottlenecks and standardisation needs for the process industry.* Tratto da https://www.spire2030.eu/harmoni

Harris, S. P. (2004). Industrial ecology as a learning process in business strategy. *Prog. Ind. Ecol.*, 1, 89–111.

Haschimoto, S. F. (2010). Realizing CO2 emission reduction through indus-trial symbiosis: a cement production case study for Kawasaki. *Resources, Conservation & Recycling*, 704-710.

He, K., & Wang, L. (2017, April). A review of energy use and energy-efficient technologies for the iron and steel industry. *Renewable and Sustainable Energy Reviews, 70*, , Pages 1022-1039.

He, M., Li, B., Zhou, W., Chen, H., Liu, M., & Zou, L. (2018). *Preparation and Characteristics of Steel Slag Ceramics from Converter Slag.* (Springer, A cura di) Berlin/Heidelberg, Germany.

HEART. (2013-2017). *LIFE 12 ENV/FR/000142 HEART - IMPROVED HEAT RECOVERY IN CLAY ROOF TILES AND BRICKS PRODUCTION.* Tratto da http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=4708&docType=pdf

Hendrik, A. a. (2002). Cement manufacture and the environment: part I: chemistry and technology. *J Ind Ecol*, 89-105.

HEROTILE. (LIFE; 2015-2019). *HEROTILE*. Tratto da www.lifeherotile.eu

HESS. (RFCS; 01/07/2023-30/06/2026). *Hybrid energy storage system using post-mining infrastructure.* https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/projects-details/43252449/101112380/RFCS2027.

HLGEEIs. (2019). *Masterplan for a competitive transformation of EU energy-intensive industries enabling a climate-neutral, circular economy by 2050 .* Tratto da https://op.europa.eu/en/publication-detail/-/publication/be308ba7-14da-11ea-8c1f-01aa75ed71a1/language-en

Hoenig, V., Koring, K., Fleiger, P., Müller, C., Palm, S., & Reiners, J. (2013). Energy efficiency in cement production; part 1. *Cement International*, 46-65.

Hoeven, D. v. (2014, Maggio 7). *ecover-pilots-new-business-model-mallorca.* Tratto da greenfutures: http://www.forumforthefuture.org/greenfutures/articles/ecover-pilots-new-business-model-mallorca

Holcim, G. (2006). *Guidelines on Co-Processing Waste Materials in Cement Production.* Offenbach, Germany; 2006: ROHLAND & more Mediengesellschaft mbH.

Howaldt, J., Kaletka, C., & Schröder, A. (2021). A Research Agenda for Social Innovation-the emergence of a research field. In *A Research Agenda for Social Innovation.* Edward Elgar Publishing.

HURRICANE. (Horizon.2.4-Digital, Industry and Space; 01/01/2024-31/12/2028). *Sector-coupling hub for circular use of thermal and industrial waste.* https://cordis.europa.eu/project/id/101138494.

HydroPick. (RFCS; 01/06/2019–30/11/2022). *Analysis and control of hydrogen content during steelmaking*. Tratto da https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/how-to-participate/org-details/967060319/project/847256/program/31061225/details

HyInHeat. (Horizon.2.4-Digital, Industry and Space; 01/01/2023-31/12/2026). *Hydrogen technologies for decarbonization of industrial heating processes.* https://cordis.europa.eu/project/id/101091456.

HYPOBRICK, L. (LIFE18 CCM/ES/001114; 2019-2022). *LIFE HYPOBRICK*. Tratto da https://lifehypobrick.eu/

I Quaderni per la Transizione Energetica: Comunità Energetiche Rinnovabili e Gruppi di Autoconsumatori #2 - Principali modelli giuridici per la costituzione delle Comunità energetiche rinnovabili. (2023, 4 18). Tratto da https://energia.regione.emilia-romagna.it/comunita-energetiche/allegati/quaderno-2_comunita-energetiche-rinnovabili.pdf/@@download/file/Quaderno%202_Comunit%C3%A0%20energetiche%20rinnovabili.pdf

I Quaderni per la Transizione Energetica: Comunità Energetiche Rinnovabili e Gruppi di Autoconsumatori. (2022, 9 22). Tratto da https://energia.regione.emilia-romagna.it/comunita-energetiche/allegati/quaderno-1-comunita-energetiche-web.pdf/@@download/file/Quaderno-comunita-energetiche-1.pdf

I2MSTEEL. (RFSR-CT-2012-00038 - 01/07/2012-31/12/2015). *Development of a new automation and information paradigm for integrated intelligent manufacturing in the steel industrybased on holonic agent technology.*

I3UPGRADE. (RFCS; 01/06/2018-31/12/2021). *Integrated and intelligent upgrade of carbon source through hydrogen addition for steel industry.* Ct No 800659.

IbD. (H2020 - SPIRE 8 - 2015 Grant Agreement no. 680565; 2015-2018). *Intensified by Design® for the Intensification of Processes involving Solids Han-dling*. Tratto da http://ibd-project.eu/

Ibn-Mohammed, T. R. (2019). Decarbonising ceramic manufacturing: A techno-economic analysis of energy efficient sintering technologies in the functional materials sector. *J. Eur. Ceram. Soc.*, 5213-5235.

ICARUS. (HORIZON.2.4 - Digital, Industry and Space; 01/01/2024 - 31/12/2027). *Increasing Circularity in process industries by upcycling secondary resources.* https://cordis.europa.eu/project/id/101138646.

ICF. (2015). Study on energy efficiency and energy saving potential in industry and on possible policy mechanisms, . *ICF Consulting Limited report, Contract no. ener/c3/2012-439/s12.666002*.

IEA. (2014, October). *"Energy use in the steel industry."*. Tratto da www.iea.org/media/workshops/2017/ieaglobalironsteeltechnologyroadmap/171120ISTRMSession2Cullen_NEW_and_APPROVED.pdf.

IES. (2018). Metals for a climate neutral Europe – a 2050 Blueprint, the Institute for European Studies (IES). *https://www.eurometaux.eu/media/1997/exec-summary-metals-2050.pdf*.

IES, 2. (2018). *Metals for a climate neutral Europe – a 2050 Blueprint, the Institute for European Studies (IES) https://www.eurometaux.eu/media/1997/exec-summary-metals-2050.pdf.*

Increasedefficiency. (Highways Agency, 2013). *Increased efficiency in the use of materials to deliver future investment,.* Tratto da http://www.highways.gov.uk/knowledge/news/increased-efficiency-in-the-use-of-materials-to-deliver-future-investment/ and https://www.gov.uk/government/organisations/highways-england

INCUBIS. (Grant agreement ID: 894800, H2020-EU.3.3.1. - Reducing energy consumption and carbon foorpint by smart and sustainable use, 2020-2023). *An Industrial Symbiosis Incubator for Maximizing Waste Heat/Cold Efficiency in Indus-trial Parks and Districts.* Tratto da https://cordis.europa.eu/project/id/894800

info(at)odyssee-mure.eu. (2001-2010). *ODYSEE-MURE Project*. Tratto da /www.odyssee-mure.eu: https://www.odyssee-mure.eu/project.html

INITIATE. (H2020-EU.2.1.5.; 01/11/ 2020–30/04/2025). *Innovative industrial transformation of the steel and chemical industries of Europe*. Tratto da https://www.initiate-project.eu/

INNOCARB. (RFSR-CT-2010-00001; 01/07/2010 - 31/12/2013). *Innovative carbon products for substituting coke on BF operation.*

InSGeP. (RFCS; 01/07/2023-30/06/2027). *Investigations of Slags from Next Generation Steel Making Processes.* https://insgep.eu/.

INSIGHT. (s.d.). Tratto da Industrial Symbiosis Facilitator – Key study based on current knowledge, skills and qualifications regarding industrial symbiosis: https://www.insight-erasmus.eu/library/reports/: https://www.insight-erasmus.eu/library/reports/

INSIGHT. (Erasmus+, 2019-2022). *Secure management Platform for Shared Process Resources.* Tratto da https://www.insight-erasmus.eu/

INSPIREWATER. (Grant agreement ID: 723702, 2016- 2020). *INSPIREWater.* Tratto da https://www.spire2030.eu/inspirewater

INSYSME, F.-S. (2013-2016). *INNOVATIVE SYSTEMS FOR EARTHQUAKE RESISTANT MASONRY ENCLOSURES IN R.C. BUILDINGS.* Tratto da https://cordis.europa.eu/project/id/606229

International Energy Agency . (2009). *Energy Technology Perspectives. Scenarios & Strategies to 2050.* Paris, France: OECD Publishing.

International Energy Agency. (2016). *Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems.* Tratto da https://www.iea.org/reports/energy-technology-perspectives-2016

International Energy Agency. (2020). *Global CO2 emissions in 2019.* Tratto da https://www.iea.org/articles/global-co2-emissions-in-2019.

International Synergies 1. (s.d.). Tratto da http://www.international-synergies.com/wp-content/uploads/2015/10/G7-Arden_Clarke-10-Year-Framework-Programme-for-SCP.pdf

International Synergies 2. (s.d.). Tratto da http://www.international-synergies.com/wp-content/uploads/2015/10/G7-Laybourn-International-Synergies.pdf

InternationalBestPractices. (Egyptian National Cleaner Production Centre (ENCPC), April 2015-May 2015). *International Best Practice for Industrial Waste Exchange – a Roadmap: Green Growth: Industrial Waste.* Tratto da https://www.iwexproject.com/download/testing/reports/1501413859-Internation-a

INTMET. (H2020; 1/02/2016-31/01/2019). *Integrated innovative metallurgical system to benefit efficiently polymetallic, complex and low grade ores and concentrates*. Tratto da https://cordis.europa.eu/project/id/689515

IPPC, I. P. (2010). *Reference Document on Best Available Techniques in the Cement, Lime and Magnesium Oxide Manufacturing Industries.*

ISAFA. (“Bando Ricerca e Innovazione In Campo Territoriale e Ambientale” No RFSR-CT-2011-00037). *Impiego della Scoria di Acciaieria come Fertilizzante in Agricoltura.*

iSlag. (G.A. 899164; 01/07/2020-31/12/2023). *Optimising slag reuse and recycling in electric steelmaking at optimum metallurgical performance through on-line characterization devices and intelligent decision support system.*

ISS. (INI, Invest Northern Ireland, 2007-ongoing). *Industrial Symbiosis Service (ISS).* Tratto da https://www.investni.com/

ITERAMS. (H2020; 01/06/2017-30/11/2020). *Integrated mineral technologies for more sustainable raw material supplydata sci-ence, recycling*. Tratto da https://cordis.europa.eu/project/id/730480/reporting

iWAYS. (H2020; 01/12/2020 – 30/11/2024). *Innovative water recovery solutions through recycling of heat, materials and water across multiple sectors*. Tratto da https://www.iways.eu/

Jiang, Y., Ling, T.-C., Shi, C., & Pan, S.-Y. (2018). Characteristics of steel slags and their use in cement and concrete-A review. *Resour. Conserv. Recycl., 136*, 187–197.

Jiao W., B. F. (2014). Toward a research agenda for policy intervention and facilitation to enhance industrial symbiosis based on a comprehensive literature review. *Journal of Cleaner Production, 67*, 14-25.

Jiao, W. a. (2014). Toward a research agenda for policy intervention and facilitation to enhance industrial symbiosis based on a comprehensive literature review. *Journal of Cleaner Production* , 14-25.

JISF’s. (2018). *Commitment to a Low Carbon Society .* Tokyo, Japan: Activities of Japanese Steel Industry to Combat Global Warming; Japan Iron and Steel Federation.

Jochem, E. (2015). energy end-use. In E. Jochem, *WORLD ENERGY ASSESSMENT: ENERGY AND THE CHALLENGE OF SUSTAINABILITY* (p. 174). United Nation Developed Program.

Johansson, M. (2015). Improved energy efficiency within the Swedish steel industry—the importance of energy management and networking. *Energy Efficiency, 8*, 713-744.

Jorge, J. (2015). Secondary zinc as part of the supply chain and the rise of EAF dust recycling. *The 19th Zinc & its Markets Seminar.* Helsinki, Finland.

Kalde, A., Demus, T., Echterhof, I., & Pfeifer, I. (2015). Determining the reactivity of biochar-agglomerates to replace fossil coal in electric arc furnace steelmaking. *The 23rd European Biomass Conference and Exhibition.* Vienna, Wien, Austria.

Karduri, R. K., & Ananth, C. (2023). Energy Efficiency in Industrial Sectors: Future Directions. *Available at SSRN 4637816*.

KATCH-e. (Erasmus+ K.A.2 – Knowledge Alliance for Higher education, 2017-2019). *Knowledge Alliance on Product-Service Development towards Circular Economy and Sustainability in Higher Education.* Tratto da http://www.katche.eu/

Kaya, M. (2016). *Recovery of metals and non-metals from electronic waste by physical and chemical recycling processes".* Waste Management, 57, 64-90.

Kern, C. (2010). Innovative Gestaltung von Geschäftsprozessen in der Konsumgüterindustrie (pp. 3–. *Die Konsumgüterindustrie.*, 3-63.

Khaerudini, D., Prakoso, G., Insiyanda, D., Widodo, H., Destyorini, F., & Indayaningsih, N. (2018). Effect of graphite addition into mill scale waste as a potential bipolar plates material of proton exchange membrane fuel cells. *Journal of Physics: Conference Series, 2018* (p. 012050). Bristol, UK: IOP Publishing.

Khaleel, M., Yusupov, Z., Ahmed, A. A., Alsharif, A., Alarga, A., & Imbayah, I. (2023). The effect of digital technologies on energy efficiency policy. *Int. J. Electr. Eng. and Sustain.*, 1-8.

Kumar, P., Singh, R., & Kumar, V. (2021). Managing supply chains for sustainable operations in the era of industry 4.0 and circular economy: Analysis of barriers. *Resources, Conservation and Recycling*, 105215.

Larsson, M. W. (2006). Improved energy and material efficiency using new tools for global optimisation of residue material flows. *Internation Journal of green energy*.

LASERFIRING. (2010-2013). *LIFE09 ENV/ES/000435, LASERFIRING - CLIMATE CHANGE ADAPTATION OF THE STRUC-TURAL CERAMICS INDUSTRY BY DECREASING THE FIRING TEMPERATURE USING LASER TECHNOLOGY.* Tratto da https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=3659

LEAP4SME. (2020). *LEAP4SME*. Tratto da CORDIS: https://cordis.europa.eu/project/id/893924/it

Lee, J. C. (2019). Comparing properties of concrete containing electric ARC furnace slag and granulated blast furnace slag. *Materials, 12*(9), 1371.

LEEWAY. (INTERREG EUROPE; 01/03/2023-31/05/2027). *LEading coopEration toWArds energy communities policies tackling energy povertY.* https://www.interregeurope.eu/leeway.

LIFECERAM. (2013-2016). *LIFE12 ENV/ES/230-LIFE CERAM – ZERO WASTE IN CERAMIC TILE MANUFACTURE.*

LIFE-CERSUDS. (2016-2019). *LIFE 15 CCA/ES/000091, CERSUDS - CERAMIC SUSTAINABLE URBAN DRAINAGE SYSTEM.* Tratto da https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=5665#RM

LIFECERSUDS. (2016-2019). *LIFE15 CCA/ES/000091, CERSUDS - CERAMIC SUSTAINABLE URBAN DRAINAGE SYSTEM .* Tratto da https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=5665#RM

LIFECLAYGLASS. (2013-2016). *LIFE12 ENV/ES/000156, LIFE CLAYGLASS - ADAPTATION TO CLIMATE CHANGE BY THE STRUCTURAL CERAMICS INDUSTRY THROUGH THE USE OF RECYCLED GLASS AS PAS-TRY.* Tratto da https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=4689&docType=pdf\

LIFEFOUNDRYTILE. (2015-2018). *LIFE Environment & Resource Efficiency LIFE14 ENV/ES/000252 Valorisation of iron foundry sands and dust in the ceramic tile production process, LIFEFOUNDRYTILE.*

LIFE-SANITSER. (2013-2017). *LIFE12ENV/IT/001095, LIFE SANITSER – SANITARYWARE PRODUCTION: USE OF WASTE GLASS FOR SAVING ENERGY AND RESOURCES.* Tratto da http://www.sanitser.eu/en/about

LightCoce. (H2020; 2019-2023). *Building an Ecosystem for the up-scaling of lightweight multifunctional concrete and ceramic materials and structures*. Tratto da https://www.lightcoce-oitb.eu/en/normal/home

Lisa Goldapple. (2016, novembre 21). *atlasofthefuture*. Tratto da Editor, Atlas of the Future (21 November 2016): https://atlasofthefuture.org/project/pay-per-lux/

LoCO2Fe. (H2020; 01/05/2015-31/10/2018). *Development of a Low CO2 Iron and Steelmaking Integrated Process Route for a Sustainable European Steel Industry*. Tratto da https://cordis.europa.eu/project/id/654013/reporting

Lombardi, D., & Laybourn, P. (2012). Redefining industrial symbiosis: Crossing academic–practitioner boundaries. *Journal of Industrial Ecology, 16*, 28-37. doi: https://doi.org/10.1111/j.1530-9290.2011.00444.x

LOOP, M. (Walloon Region;). *Mineral LOOP.* https://www.carmeuse.com/eu-en/mineral-loop.

López-Díaz, A., Ochoa-Díaz, R., & Grimaldo-León, G. (2018). Use of bof slag and blast furnace dust in asphalt concrete: An alternative for the construction of pavements. *DYNA , 85*, 24-30.

Luciano, A. G. (2016). Potential improvement of the methodology for industrial symbiosis implementation at regional scale. *Waste and biomass valorization*, 1007-1015.

Lundkvist, K., Rosendahl, S., Sandberg, E., Haase, B., Stemne, J., Peltola, P., & Eriksson, R. (2019). Case study of industrial symbiosis for improved residual material utilisation in the steel industry. *Matériaux & Techniques, 107*(509).

M. Chertow, a. Y. (2010). Assessing Collective Firm Behavior: Comparing Industrial Symbiosis with Possible Alternatives for Individual Companies in Oahu, HI. *Bus. Strateg. Environ. 20*, 266–280.

M2DESCO. (Horizon-CL4-2023-RESILIENCE-01; 01/01/2024-31/12/2027). *Computational Multi-Models Enabled Design of Safe & Sustainable Multi-Component High-Entropy Coatings.*

Madias, J. (2017). A review on recycling of refractories for the iron and steel industry. *Proceedings of the UNITECR 2017—15th Biennial Worldwide Congress.* Santiago, Chile.

Madlool, N. S. (2013). An overview of energy savings measures for cement industries. *Renew. Sustain. Energy Rev.*, 18-29.

MAESTRI. (Horizon 2020, SPIRE Grant agreement No 680570, 2015-2019). *Resorce and Energy Efficiency for Process Industries.* Tratto da https://maestri-spire.eu/wp-content/uploads/2018/01/MAESTRI-D4_1_v2_rev.pdf

MAGF. (2014-2017). *MAGF - MICROWAVE ASSISTED GAS FIRING, Regional project.* Tratto da https://www.dti.dk/specialists/masonry-and-tile-roofing/ceramic-production-using-microwaves/23527,3?cms.query=MAGF

Malinauskaite, J., Jouhara, H., Ahmad, L., Milani, M., Montorsi, L., & Venturelli, M. (2019). Energy efficiency in industry: EU and national policies in Italy and the UK. *Energy*, 255–269.

Mallawaarachchi, H., Karunasena, G., Sandanayake, Y., & Liu, C. (2023). Conceptualising a Model to Assess the Optimum Water Flow of Industrial Symbiosis (IS). *Sustainability*, 8627.

Manojlović, V., Kamberović, Ž., Korać, M., & Dotlic, M. (2022). Machine learning analysis of electric arc furnace process for the evaluation of energy efficiency parameters. *Applied Energy*, 118209.

Mapelli, C., Dall'Osto, G., Mombelli, D., Barella, S., & Gruttadauria, A. (2022). Future scenarios for reducing emissions and consumption in the Italian steelmaking industry. *steel research international*, 2100631.

Marchiori, F., Belloni, A., Benini, M., Cateni, S., Colla, V., Ebel, A., . . . Vignali, A. (2017). “Integrated dynamic energy management for steel production”. *Energy Procedia, 105*, 2772-77.

Marchiori, F., Benini, M., Cateni, S., Colla, V., Ebel, A., Neuer, M., . . . Vignali, A. (2018). Agent-based approach for energy demand-side management. *Stahl und Eisen, 138* (2), 25-29.

Marconi. (2018). *“An approach to favor industrial symbiosis: the case of waste electrical and electronic equipment”.* Procedia Manufacturing, 21, 502-509.

Marisa Isabel Almeida, A. C. (2016). Environmental profile of ceramic tiles and their potential for improvement. *Journal of Cleaner Production*, 583-593.

Marra A., C. A. (2018). *“The recovery of metals from WEEE: state of the art and future perspectives”.* Global NEST Journal, Vol 20, No 4, pp 679-694.

Matino, I., Colla, V., & Baragiola, S. (2017). Electric energy consumption and environmental impact in unconventional EAF steelmaking. *Energia Procedia, 105*, 3636-3641.

Matino, I., Colla, V., & Baragiola, S. (2017). Quantification of energy and environmental impacts in uncommon electric steelmaking scenarios to improve process sustainability. *Applied Energy, 207*, 543-552.

Matino, I., Colla, V., & Branca, T. A. (2020). Addressing the right by-product recovery steps in steelmaking chain: support tools for slag recovery, recycle and reuse. *Resi4Future web workshop.* ESTEP.

Matino, I., Dettori, S., Castellano, A., Matino, R., Mocci, C., Vannocci, M., . . . Wolff, A. (2020). Machine Learning-Based Models for Supporting Optimal Exploitation of Process Off-Gases in Integrated Steelworks. In *Cybersecurity workshop by European Steel Technology Platform* (p. 104-118). Springer.

Matino, I., Dettori, S., Colla, V., Weber, V., & Salame, S. (2019). Application of Echo State Neural Networks to forecast blast furnace gas production: pave the way to off-gas optimized management. *Energia Procedia, 158*, 4037-4042.

Matino, I., Dettori, S., Colla, V., Weber, V., & Salame, S. (2019). Forecasting blast furnace gas production and demand through echo state neural network-based models: Pave the way to off-gas optimized management. *Applied Energy*, 113578.

Matino, I., Dettori, S., Colla, V., Weber, V., & Salame, S. (2019). Two innovative modelling approaches in order to forecast consumption of blast furnace gas by hot blast stoves. *Energia Procedia*, 4043-4048.

Matino, I., Dettori, S., Colla, V., Zaccara, A., Petrucciani, A., Weber, V., . . . Wolff, A. (2019). “Advanced modelling for forecasting off-gas, steam and electricity production and demand in integrated steelworks: the GASNET model library”,. *European Steel Days ESTAD.* Dusseldorf (Germany).

Matino, I., Fornai, B., Colla, V., Romaniello, L., & Rosito, F. (2017). Water process integration: assessment of an ultrafiltration and reverse osmosis based treatment to regenerate cokemaking area wastewater. *European Steel Days ESTAD.* Vienna.

MaxH2DR. (Horizon-CL4-2021-Twin-Transition-01-18; 01/06/2022-31/05/2026). *Maximise H2 Enrichment in Direct Reduction Shaft Furnaces.* https://cordis.europa.eu/project/id/101058429.

Mazur, D., Kay, J., Mazur, K., & Venne, B. (2018). The value of integrating power and process for the metals industry. *Iron and Steel Technology, 15*(5), 56-62.

McDonald, I., & Werner, A. (2014). Dry slag granulation with heat recovery. *AISTech—Iron and Steel Technology Conference Proceedings (Association for Iron and Steel Technology, AISTECH)*, *1*, p. 467–4. Indianapolis, IN, USA.

McLellan, B., Corder, G., Giurco, D., & Ishihara, K. (2012). Renewable energy in the minerals industry: a review of global potential. *Journal of Cleaner Production*, 32-44.

METABUILDING. (H2020; 2020-2023). *METABUILDING*. Tratto da https://www.metabuilding.com/about/

Miller, G. T., & Spoolman, S. (2011). *Living in the environment: principles, connections, and solutions.* Cengage Learning. Tratto da https://en.wikipedia.org/wiki/Symbiosis.

MI-ROG. (National Government support – Highways England, 2013-ongoing). *Major Infrastructure - Resource Optimisation Group,.* Tratto da https://www.aecom.com/projects/circular-economy-action-major-infrastructure-resources-optimisation-group-mi-rog/

ModHEATech. (Horizon.2.4-Digital, Industry and Space; 01/03/2023-28/02/2026). *Modular HEATing Technology through renewable resources for steel production.* https://cordis.europa.eu/project/id/101092234.

Mohammed, T., Aa, H., Ma, E.-A., & Khm, E.-M. (2012). Coral rehabilitation using steel slag as a substrate. *Int. J. Env. Prot. , 2*, 1-5.

Mokhtar, A. N. (2020). A decision support tool for cement industry to select energy efficiency measures. *Energy Strategy Reviews*, 100458.

Monteiro, H., Cruz, P. L., & Moura, B. (2022). Integrated environmental and economic life cycle assessment of improvement strategies for a ceramic industry. *Journal of Cleaner Production*, 131173.

Morán, L., Sbarbaro, D., Ortega, F., & Espinoza, J. (2019). Electrical energy consumption characterization of open-pit mining and mineral processing operations towards the use of re-newable energy sources. In *2019 IEEE Industry Applications Society* (p. 1-6). IEEE.

MORSE. (H2020; 1/10/2017–28/02/2022). *Model-based optimisation for efficient use of resources and energy*. Tratto da https://www.aspire2050.eu/morse

MultiSensEAF. (RFCS; 01/07/2023-31/12/2026). *Multi-Sensor Systems for an optimized EAF.* https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/projects-details/43252449/101112488/RFCS2027.

MW4REMAM. (Horizon Europe-ERAMIN3; 15/04/2022-31/12/2024). *Microwave enhanced recovery of REEs and plastic from WEEE and re-use in Additive Manufacturing of novel magnetic components.* https://imnr.ro/wp/proiecte/recuperarea-intensificata-cu-microunde-a-ree-si-a-plasticului-din-deee-si-reutilizarea-la-fabricarea-aditiva-a-unor-noi-componente-magnetice-acronim-mw4remam/.

NanoCeramiCO2. (2014-2017). *LIFE13 ENV/ES/00375, NanoCeramiCO2 - Climate Change Prevention by the inclusion of nanoparticles in clays for the reduction of Ceramic Industry CO2 emissions.* Tratto da https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=5076

NationalIndustrialSymbiosisProgramme. (International development-France, 2015-2017). *National Industrial Symbiosis Programme (PNSI - France).* Tratto da https://www.ademe.fr/programme-national-synergies-interentreprises

NEOSAWARE. (H2020, 01/12/2019-31/05/2020). *Modelling software platform for ceramic body optimization*. Tratto da https://cordis.europa.eu/project/id/887621/reporting

Neves, A., Godina, R., Azevedo, S., & Matias, J. (2019). A comprehensive review of industrial symbiosis. *Journal of Cleaner Production*.

Neves, A., Godina, R., G. Azevedo, S., Pimentel, C., & C.O. Matias. (2019). The Potential of Industrial Symbiosis: Case Analysis and Main Drivers and Barriers to Its Implementation. *Sustainability , 11*, 7095.

NEWSKIN. (H2020; 2020-2024). *NEWSKIN*. Tratto da https://www.newskin-oitb.eu/theproject/

NextGen. (H2020; June 2019-May 2022). Tratto da https://www.kwrwater.nl/en/actueel/the-next-generation-of-managing-our-most-important-resource/

Nguyen, H., Lu, D., & Le, S. (2018). Investigation of using steel slag in hot mix asphalt for the surface course of flexible pavements. IOP Conference Series: Earth and Environmental Science, 2018; IOP Publishing: Bristol, UK, 2018; p. 012022. *IOP Conference Series: Earth and Environmental Science, 2018* (p. p. 012022). Bristol, UK: IOP Publishing.

NKL. (National (BE) GreenWin; 02/2022–01/2026). *Neutral Keto Lime.* https://eula.eu/wp-content/uploads/2023/09/EuLA-Innovation-Booklet-3.0-EN-WEB.pdf.

Notarnicola, T. R. (2016). Industrial symbiosis in the Taranto industrial district: current level,. *Journal of Cleaner Production 122*, 133-143.

NYMPH. (H2020-ERANEt-MANUNET; 01/12/2020-30/11/2022). *Novel technology for manufacturing a multifunctional hybrid membrane for advanced purification of wastewaters.* www.imnr.ro/nymph.

O'Driscoll, M. (2017). *Recycling Refractories.* Tratto il giorno June 2020 da http://imformed.com/wp-content/uploads/2017/07/IMFORMED-Refractory-Recycling-Glass-Int-Mar-2016.pdf

OECD, (. (2018). *Global Materials Outlook to 2060: Economic Drivers and Environmental.*

OFFGAS. (RFSR-CT-2006-00004 01/07/2006-30/06/2009). *Improved EAF process control using on-line offgas analysis.*

Oge, M., Ozkan, D., Celik, M., Gok, M., & Karaoglanli, A. (2019). An overview of utilization of blast furnace and steelmaking slag in various applications. *Mater. Today Proc. , 11*, 516–525.

Olaru, M. M. (2022). MICROWAVE ASSISTED SOLUTION COMBUSTION SYNTHESIS FOR Li RECOVERY FROM SECONDARY SOURCES. *5th International Conference on Emerging Technologies in Materials Engineering EMERGEMAT*, (p. 34).

OMR. (H2020; 01/04/2020-31/12/2022). *X-Ray Fluorescence, Shape recognition & Machine Learning for Efficient and Economic Recycling of Mixed Metals from Co-mingled Waste*. Tratto da https://cordis.europa.eu/project/id/945922/reporting

Omran, M., Fabritius, T., & Heikkinen, E.-P. (2019). Selective zinc removal from electric arc furnace (EAF) dust by using micro-wave heating. *J. Sustain. Metall. , 5*, 331–340.

On the Road to Climate Neutrality 2050. (Social Dialogue; 02/2021-05/2023). *On the Road to Climate Neutrality 2050 – the Role of Social Partners in the Decarbonisation of the Chemical, Pharmaceutical, Rubber and Plastics Industries.* https://news.industriall-europe.eu/documents/upload/2023/7/638245789206351555_Final__report_EN_chemneut.pdf .

OPTDESLAG. (RFSR-CT-2010-00005; 1/07/2010-30/06/2013). *Increased yield and enhanced steel quality by improved deslagging and slag conditioning (.*

OPTISCRAPMANAGE. (RFSR-CT-2014-00007 1/07/2014-30/06/2017). *Optimization of scrap charge management and related process adaptation for EAF performances.*

Paquin RL, H.-G. J. (2012). The evolution of facilitated industrial symbiosis. *Journal of industrial Ecology, 16*(1), 83-93.

Paredes Sánchez, J. (2018). Solar energy applications in mining: a case study. In *Energy efficiency in the minerals industry* (p. 273-285). Springer, Cham.

Pasetto, M., & Baldo, N. (2018). Re-use of industrial wastes in cement bound mixtures for road construction. Environ. Eng. Manag. J. 2018, 17, 417–426. *Environ. Eng. Manag. J., 17*, 417–426.

Pears, A. (2020). Energy Efficiency Education and Training: Australian Lessons on What Employers Want—Or Need . *Energies*, 2386.

Peters K., M. E. (2019). The European steel technology platform's strategic research agenda: a further step for the steel as backbone of EU resource and energy intense industry sustainability. *METALLURGIA ITALIANA, 1*(15), 5-17.

Petersen, M. (2017). *Considering Sustainability in the Development of Consumer Goods.* Harburg: Vom Promotionsausschuss der Technischen Universität Hamburg-.

PHEIDIAS. (2022-2024). *AN INNOVATIVE HYDROMETALLURGICAL RECYCLING SYSTEM FOR PGMs RECOVERY.* https://pheidias.eu/.

Pistocchi, C., Ragaglini, G., Colla, V., Branca, T., Tozzini, C., & Romaniello, L. (2017). Exchangeable sodium percentage decrease in saline sodic soil after basic oxygen furnace slag application in a lysimeter trial. *J. Environ. Manag. , 203*, 896–906.

Piticescu, R.-R., Slobozeanu, A. E., Valsan, S. N., Ciobota, C. F., Ghita, A.-N., Motoc, A. M., . . . Prakasam, M. (2021). Hydrothermal Synthesis of Nanocrystalline ZrO2-8Y2O3-xLn2O3 Powders (Ln = La, Gd, Nd, Sm): Crystalline Structure, Thermal and Dielectric Properties. *Materials*, 7432; https://doi.org/10.3390/ma14237432.

Plan, C. A. (2020). *Circular Aluminium Action Plan.* Tratto da https://www.european-aluminium.eu/media/2929/2020-05-13-european-aluminium_circular-aluminium-action-plan.pdf

PLUS, I. (INTERREG EUROPE; 11/2020-05/2024). *IMPULSE PLUS.* https://impulse-project.eu/project-introduction-objectives/ .

POLYNSPIRE. (H2020; Grant Agreement no. 820665, 2018-2022). *Demonstration of Innovative Technologies towards a more Efficient and Sustain-able Plastic Recycling.* Tratto da https://www.polynspire.eu/

Porzio, G. F., Colla, V., Fornai, B., Vannucci, M., Larsson, M., & Stripple, H. (2014). Process Integration analysis for innovative environmentally friendly recovery and pretreatment of steel scrap. *Special issue 17th Conference on Process Integration, modelling and optimization for energy saving and pollution reduction, PRES2014 AIDC(2013).* Prague, Czech Republic.

Porzio, G. F., Colla, V., Matarese, N., Gianluca, N., Branca, T. A., Amato, A., . . . Bergamasco, M. (2014). Process integration in energy and carbon intensive industries: an example of exploitation of optimization techniques and decision support. *70*(1), 1148-1155.

Porzio, G., Colla, V., Fornai, B., Vannucci, M., Larsson, M., & Stripple, H. (2016). Process integration analysis and some economic-environmental implications for an innovative environmentally friendly recovery and pre-treatment of steel scrap. *Appl. Energy, 161*, 656–672.

PowGETEG. (GA Number: RFSR – CT – 2015 – 00028 - 01/07/2015 – 30/06/2019). *Power generation from hot waste gases using thermoelectrics.*

Process and apparatus for the thermal treatment of refinery sludge. us2012184797 (a1): us8969647 (b2); 03/03/2015. (s.d.). Tratto da https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2011007231

PROSUM, 2. (2017). *Prospecting Secondary Raw Materials in the Urban Mine and mining wastes (ProSUM) - Final Report, ISBN: 978-92-808-9060-0 (print), 978-92-808-9061-7 (electronic).*

PROTECT. (RFSR-CT-2010-00004; 01/07/2010-31/12/2013). *Processes and technologies for environmentally friendly recovery and treat-ment of scrap.*

PSP-BOF. (RFCS-CT-2013-00037; 01/07/2013-31/12/2016). *Removal of Phosphorous from BOF Slag.*

Qian, Y. (2016). Sustainable Management of Water Resources. Volume 2, Issue 1, Pages 23-25.

Qiu, W., Zhao, X., Wu, H., & Ren, S. (2024). The role of industrial symbiosis on consumer demand under ecological carbon fixation: Evidence from the energy industry. *Managerial and Decision Economics*.

R3VOLUTION. (HORIZON-CL4-2023-TWIN-TRANSITION-01;01/01/2024-31/12/2027). *A rEVOLUTIONary approach for maximising process water REuse and REsource REcovery through a smart, circular and integrated solution.* https://cordis.europa.eu/project/id/101138245.

Ramin, E., Faria, L., Gargalo, C. L., Ramin, P., Flores-Alsina, X., Andersen, M. M., & Gernaey, K. V. (2024). Water innovation in industrial symbiosis-A global review. *Journal of Environmental Management*, 119578.

Ramsheva, Y., & Remmen, A. (2018). Industrial symbiosis in the cement industry-Exploring the linkages to circular economy. *1st International Conference on Technologies & Business Models for Circular Economy* (p. 35-54). University of Maribor Press.

Ranieri, A. (2013). *Skills for a Low-Carbon Europe: The Role of VET in a Sustainable Energy Scenario. Synthesis Report. Research Paper No 34.* Cedefop-European Centre for the Development of Vocational Training .

Rapier, R. (2020). *Fossil Fuels Still Supply 84 Percent of World Energy—And Other Eye Openers from BP's Annual Review.* Tratto da https://www.forbes.com/sites/rrapier/2020/06/20/bp-review-new-highs-in-global-energy-consumption-and-carbon-emissions-in-2019/?sh=125959bd66a1

ReActiv. (H2020, 2021-2024). *Industrial Residue Activation for sustainable cement production.*

RecHycle. (Horizon.2.4-Digital, Industry and Space; 01/06/2022-31/05/2026). *Recycling renewable hydrogen for climate neutrality.* https://cordis.europa.eu/project/id/101058692.

RECODE. (H2020; 1/08/2017-31/07/2022). *Recycling carbon dioxide in the cement industry to produce added-value ad-ditives: a step towards a CO2 circular economy*. Tratto da https://cordis.europa.eu/project/id/768583/reporting

RECONMATIC. (Horizon Europe; 2022-2026). *Automated solutions for sustainable and circular construction and demolition waste management*. Tratto da https://futureneeds.eu/case-studies/waste-management-reconmatic/

RECONSTRUCT. (Horizon-CL6-2022; 01/06/2023-31/05/2027). *A Territorial Construction System for a Circular Low-Carbon Built Environment.* https://cordis.europa.eu/project/id/101082265.

RECYCLEART. (ERASMUS+, 2015-2016). *RECYCLE ART.* Tratto da https://ec.europa.eu/programmes/erasmus-plus/projects/eplus-project-details/#project/2015-2-IT03-KA105-006111

RED_SCOPE. (KIC EIT Raw Materials 2016-2019). *Recovery of Effluent Discharge for Sustainable Copper Processing in Europe.*

REDILP. (FP6-SME Ref.508714; 01/11/2004-30/04/2007). *Recycling of EAF dust by an integrated leach-grinding process.*

REDiRECT. (Italian Ministry of Enterprises and Made in Italy (MIMIT); 01/10/2020-30/09/2023). *REDuce REuse Ceramic Tiles.* https://sites.google.com/view/redirect-project-en/home-page.

REDUCER. (2012-2014). *Sustainable Industry Low Carbon Scheme I (SILC), Reducer- Reduction of carbon dioxide emissions in the ceramic manufacturing process.* Tratto da https://ec.europa.eu/docsroom/documents/33440

REFFIPLANT. (RFCS-CT-2012-00039; 01/07/2012-31/12/2015). *Efficient use of resources in steel plants through process integration.*

Reijnders, L. (2007). The Cement Industry as a Scavenger in Industrial Ecology and the Management of Hazardous Substances. *J Ind Ecol*, 15-25.

Reijonen, I., & Hartikainen, H. (2018). Risk assessment of the utilization of basic oxygen furnace slag (BOFS) as soil liming ma-terial: Oxidation risk and the chemical bioavailability of chromium species. Environ. Technol. Innov. 2018, 11, 358–370. *Environ. Technol. Innov. , 11*, 358–370.

REINJECT. (RFCS; 01/03/2024-31/05/2028). *Flexible reinjection of Secondary Raw Materials by Leveraging Digital Disruption and Waste Valorisation.* https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/projects-details/43252449/101140348/RFCS2027.

Reiter, W., Rieger, J., Raupenstrauch, H., Cattini, L., Maystrenko, N., Kovalev, D., . . . Mitrofanov, A. (2023). Recovery of valuable materials with the RecoDust process. *Metals*, 1191.

RELiEF. (Horizon Europe; 01/07/2022-30/06/2025). *Recycling of Lithium from Secondary Raw Materials and Further.* https://lithium-relief.eu/.

REMEB. (H2020-EU.3.5.4. H2020-WATER-2014-two-stage - Grant agreement ID: 641998; 2015-2018). *Eco-friendly ceramic Membrane Bioreactor (MBR) based on recycled agricultur-al and industrial wastes for waste water reuse*. Tratto da https://cordis.europa.eu/project/id/6419

ReMFra. (Horizon.2.4-Digital, Industry and Space; 01/12/2022-31/05/2026). *REcovering Metals and Mineral FRAction from steelmaking residues.* https://cordis.europa.eu/project/id/101058362.

REMOVAL. (H2020, 2018-2022). *Removing the waste streams from the primary Aluminum production in Europe.* Tratto da https://www.removal-project.com/

Ren21. (2019). *Renewables global status report.* Tratto da www.ren21.net/gsr-2019/

RENSKILL. (s.d.). Tratto da https://www.deusto.es/cs/Satellite/deusto/en/university-deusto/deusto-awards-4-new-research-projects-for-their-positive-impact-and-social-transformation/noticia

RESLAG. (H2020 GA No. 642067; 01/09/2015 to 31/07/2019). *Turning waste from steel industry into a valuable low cost feedstock for energy intensive industry.*

RESURGENCE. (Horizon.2.4-Digital, Industry and Space; 01/12/2023-30/11/2027). *INDUSTRIAL WATER CIRCULARITY: REUSE, RESOURCE RECOVERY AND ENERGY EFFICIENCY FOR GREENER DIGITISED EU PROCESSES.* https://cordis.europa.eu/project/id/101138097.

RETECH. (H2020-ERAMIN2; 01/08/2020-31/12/2024). *Recovery of rare earth elements from complex ores in Turkey and their potential use in high tech industrial applications.* www.imnr.ro/retech.

REVaMP. (H2020/SPIRE, 01/01/2020–30/06/2023). *Retrofitting Equipment for Efficient Use of Variable Feedstock in Metal Making Processes*. Tratto da https://revamp-project.eu/

REWACER. (Valencian Innovation; 2019-2020). *REWACER*.

ReWINDS:. (PR-FESR; 2021-2027). *Recycling of Waste into New Demonstrated Sustainable Solutions Financial plan.* https://certimac.it/en/projects/rewinds.

Rezessy, S. a. (2011). Voluntary agreements in the field of energy efficiency and emission reduction: Review and analysis of experiences in the European Union. *Energy Policy* , 7121-7129.

REZIN. (FP5-G5RD-CT-2002-00652; 1/04/2002 – 31/03/2005). *Elimination of zinc ferrite.*

RIHANNE. (RFCS; 01/06/2019–30/11/2022). *Reliable Blast Furnace Hearth Management*. Tratto da https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/how-to-participate/org-details/967060319/project/847332/program/31061225/details

RIMFOAM. (RFSR-CT-2014-00008; 1/07/2014-30/06/2017). *Recycling of industrial and municipal waste as slag foaming agent in EAF.*

RIMFOAM. (RFSR-CT-2014-00008-1/07/2014-30/06/2017). *Recycling of industrial and municipal waste as slag foaming agent in EAF.*

RISERS. (Horizon Europe; 01/01/2024-31/12/2026). *A Roadmap for Industrial Symbiosis Standardization for Efficient Resource Sharing.*

Rosendahl, S., Lundkvist, K., Haase, B., Stemne, J., Andersson, L., & Eriksson, R. (2019). Establishing an industrial symbiosis – key factors and time aspects in steel industry. *Matériaux & Techniques, 107*(508).

Rossetti di Valdalbero, D. (2017). *The Future of European Steel—Innovation and Sustainability in a Competitive World and EU Circular Economy.* Bruxelles, Belgium: European Commission.

Rotatori, D. E. (2020). The evolution of the workforce during the fourth industrial revolution. *Human Resource Development International* , 1-12.

Roudier, S., Sancho, L. D., Remus, R., & Aguado-Monsonet, M. (2013). *Best Available Techniques (BAT) reference document for iron and steel production: Industrial emissions directive 2010/75/EU: integrated pollution prevention and control.* Seville: Joint Research Centre.

SafeDewPoint. (RFCS; 1/07/2019–31/12/2022). *Acid dew point and corrosion sensors for dynamic waste heat recovery from steel mill flue gases*. Tratto da https://www.bfi.de/en/projects/safedewpoint-acid-dew-point-and-corrosion-sensors-for-dynamic-waste-heat-recovery-from-steel-mill-flue-gases/

Saleh, T. A. (2022). Global trends in technologies and nanomaterials for removal of sulfur organic compounds: Clean energy and green environment. *Journal of Molecular Liquids, 359*, 119340.

Saranya, P., Nagarajan, P., & Shashikala, A. (2018). Eco-friendly Ggbs concrete: A state-of-the-art review. *IOP Conference Series: Materials Science and Engineering* (p. 012057). Bristol, UK: IOP Publishing.

SCALE. (H2020, 2016-2021). *Production of Scandium compounds and Scandium Aluminum alloys from European metallurgical by-products.* Tratto da http://scale-project.eu/

SCALER. (H2020 SPIRE Grant Agreement n. 768748, 2017-2020). *Scaling European Resources with Industrial Symbiosis.*

Schilling, R. (2012). Manufacturing Network Development in Fast-Moving Consumer Goods. *Hamburg: Kovač, Diss. Universität Eichstätt-Ingolstadt,*.

Schöneberg, K., Homann, B., Ballaire, J., & Kessaria, S. (2023). *On the Road to Climate Neutrality 2050–the Role of Social Partners in the Decarbonisation of the Chemical, Pharmaceutical, Rubber and Plastics Industries.* Tratto da https://news.industriall-europe.eu/documents/upload/2023/7/638245789206351555_Final__report_EN_chemneut.pdf

Schröder, A. J., Cuypers, M., & Gotting, A. (2024). From Industry 4.0 to Industry 5.0: The Triple Transition Digital, Green and Social. In *Industry 4.0 and the Road to Sustainable Steelmaking in Europe: Recasting the Future* (p. 35-51). Cham: Springer International Publishing.

Schwarz, E. J., & Steininger, K. W. (1997). Implementing nature's lesson: the industrial recycling network enhancing regional development. *Journal of Cleaner Production, 5*, 47-56.

sEEnergies. (s.d.). *Quantification of synergies between Energy Efficiency First Principle and renewable energy systems for 2050 decarbonisation*. Tratto da https://www.seenergies.eu/

Sellitto, M., & Murakami, F. (2018). Industrial symbiosis: A case study involving a steelmaking, a cement manufacturing, and a zinc smelting plant. *Chem. Eng. Trans. , 70*, 211–216.

SHAREBOX. (H2020 (SPIRE-06-2015) Grant Agreement No: 680843, 2015-2019). *Secure management Platform for Shared Process Resources.* Tratto da http://sharebox-project.eu/

SHERPA, M. (INTERREG MED; 2023). *SHared knowledge for Energy Renovation in buildings by Public Administrations.* https://sherpa.interreg-med.eu/.

SHOCOM. (RFSR-CT-2005-00001, 01/07/2005-31/12/2008). *Short term CO2 mitigation for steelmaking.*

SIDERWIN project. (s.d.). Tratto da https://www.siderwin-spire.eu/

SILIFE. (LIFE14 ENV/ES/00023, 2015-2019). *PRODUCTION OF QUARTZ POWDERS WITH REDUCED CRYSTALLINE SILICA TOXICITY*. Tratto da http://www.silife-project.eu/

SIMVAL. (Agencia Valenciana de Innovaciòn (AVI)- regional programme, 2018-2019). *Estrategia hacia una Economía Circular en la Comunitat Valenciana a través de una Plataforma que fomente la Simbiosis Industrial (Strategy towards a Circular Economy in the Valencia Region through s Platform to promote Industrial Symbiosis).*

Skaf, M., Pasquini, E., Revilla-Cuesta, V., & Ortega-López, V. (2019). Performance and durability of porous asphalt mixtures manufactured exclusively with electric steel slags. *Materials , 12*, 3306.

SLACON. (RFSR-CT-2012-00006; 1/07/2012-31/12/2015). *Control of slag quality for utilisation in the construction industry.*

SLAGFERTILISER. (RFCS-CT-2011-00037; 01/07/2011-30/06/2015). *Impact of long-term application of blast furnace and steel slags as liming materials on soil fertility, crop yields and plant health.*

Slagreus. (RFCS-CT-2019-846260; 1/06/2019-30/11/2022). *Reuse of slags from integrated steelmaking.*

SLASORB. (RFSP-CT-2009-00028; 01/07/2009 - 30/06/2012). *Using slag as sorbent to remove phosphorus from wastewater.*

SMARTREC. (H2020, 2016-2019). *Developing a standard modularised solution for flexible and adaptative integration of heat recovery and thermal storage capable of recovery and management of waste heat.* Tratto da http://www.smartrec.eu/

Sommer, K. (2020, March). *Study and portfolio review of the projects on industrial symbiosis in DG Research and Innovation: Findings and recommendations.* Tratto da https://ec.europa.eu/info/publications/study-and-portfolio-review-projects-industrial-symbiosis-dg-research-and-innovation-findings-and-recommendations_en.

Sommer, K. H. (Directorate-General for Research and Innovation (European Commission), 2020-03-09). *Study and portfolio review of the projects on industrial symbiosis in DG Research and Innovation: Findings and recommendations industrial symbiosis.*

Sooriyaarachchi, T. M.-T. (2015). Job creation potentials and skill requirements in, PV, CSP, wind, water-to-energy and energy efficiency value chains. *Renewable and Sustainable Energy Reviews*, 653-668.

SOST-RCD. (Valencian Innovation Agency; 24 months). Tratto da https://www.itc.uji.es/en/el-proyecto-sost-rcd-convierte-residuos-deconstruccion-y-demolicion-en-recursos-para-una-construccion-mas-sostenible/

S-PARCS. (H2020-EE-18-2017 Grant Agreement No. 785134, 2018-2021). *Envisioning and Testing New Models of Sustainable Energy Cooperation and Services in Industrial Parks.* Tratto da https://www.sparcs-h2020.eu/

SPIRE. (2020, March). *P4Planet 2050 Roadmap.* Tratto da www.spire2030.eu: www.spire2030.eu

SPOTVIEW. (H2020; 03/10/2016-02/04/2020). *Sustainable Processes and Optimized Technologies for Industrially Efficient Water Usage*. Tratto da https://cordis.europa.eu/project/id/723577

SPRING. (H2020-IND-CE-2016-2017/H2020-SPIRE-2017; Grant Agreement No.767412, 2017-2019). *Setting the framework for the enhanced impact of SPIRE projects.* Tratto da https://www.spire2030.eu/spring

SRS. (POR FESR 2014/2020 – ACTION 1.3.a - COLLABORATIVE RESEARCH 2016-2018). *Smart system for steel slag management.*

Standardisation, E. C. (2018). *Industrial Symbiosis: Core Elements and Implementation.* Workshop Agreement. December. Tratto da ftp://ftp.cencenelec.eu/EN/ResearchInnovation/CWA/CWA17354.pdf

START. (Ministry of Enterprises and Made in Italy (MIMIT); 01/05/2023-30/04/2026). *SusTainable dAta-dRiven manufacTuring.* https://www.en.start.gresmalt.it/home-page.

Statista. (2020). Worldwide refineries -Capacities. *Statista*.

STEELANOL. (H2020-EU.3.3.-SOCIETAL CHALLENGES-Secure, clean and efficient energy; 01/05/2015-31/03/2024). *Production of sustainable, advanced bio-ethANOL through an innovative gas-fermentation process using exhaust gases emitted in the STEEL industry.* http://www.steelanol.eu/en.

Steelanol project . (s.d.). Tratto da http://www.steelanol.eu/en

STEPWISE. (H2020; 1/05/2015-30/04/2019). *SEWGS Technology Platform for cost effective CO2 reduction the in the Iron and Steel Industry* . Tratto da https://cordis.europa.eu/project/id/640769

STORM. (EIT-Raw Mate-rials KIC). *Industrial Symbiosis for the Sustainable Management of Raw Materials.* Tratto da http://www.storm-eitrm.eu/

Sucic, B. P. (2017). An education and training program for energy managers in Slovenia–Current status, lessons learned and future challenges. *Journal of Cleaner Production* , 3360-3369.

Suda, A., Yamaguchi, N., Taniguchi, H., & Makino, T. (2018). Arsenic immobilization in anaerobic soils by the application of by-product iron materials obtained from the casting industry. *Soil Sci. Plant Nutr. , 64*, 210-217.

Sun, Y., Zhang, Z., Liu, L., & Wang, X. (2015). Heat recovery from high temperature slags: A review of chemical methods. *Energies , 8*, 1917–1935.

Suopajärvi, H., Umeki, K., Mousa, E., Hedayati, A., Romar, H., Kemppainen, A., . . . Norberg, N. (2018). Use of biomass in integrated steelmaking–status quo, future needs and comparison to other low-Co2 steel produc-tion technologies. *Appl. Energy , 213*, 384–407.

SUPERHERO, L. (LIFE19 CCA/IT/001194, 2020-2025). *Energy-efficient roofs for sustainable low-cost climate adaptation*. Tratto da www.lifesuperhero.eu

SUPERMAT. (Horizon 2020 The EU Framework Programme for Research and Innovation European H2020-EU.4.b. - Twinning of research institutions, 2016-2018). *The virtual centre for integration of innovative synthesis and processing methods for sustainable advanced materials operating under extreme conditions.* Tratto da http://imnr.ro/supermat/

SUPREME. (H2020; 01/09/2017-31/12/2020). *Sustainable and flexible powder metallurgy processes optimization by a holistic reduction of raw material resources and energy consumption*. Tratto da https://cordis.europa.eu/project/id/768612/reporting

SuSteel project . (s.d.). Tratto da https://www.k1-met.com/non_comet/susteel

SYMBIOPTIMA. (H2020; 01 September 2015 - 28 February 2019). *Human-mimetic approach to the integrated monitoring, management and optimization of a symbiotic cluster of smart production units.* https://cordis.europa.eu/project/id/680426/es. Tratto da https://cordis.europa.eu/project/id/680426

SYMBY. (INTERREG EUROPE). *Industrial Symbiosis for Regional Sustainable Growth and a Resource Efficient Circular Economy I.* Tratto da https://www.interregeurope.eu/symbi/

SYMPIOPTIMA. (H2020-EU.2.1.5.301 September 2015- 28 February 2019). *Human-mimetic approach to the integrated monitoring, management and optimization of a symbiotic cluster of smart production units.* https://cordis.europa.eu/project/id/680426/es.

TABASCO. (RFSR-CT-2011-00028 01/07/2011-30/06/2014). *Thermal bridging atlas of steel construction for improved energy efficiency of buildings.*

TASIO. (H2020 G.A 637189; 2014-2019). *Waste Heat Recovery for Power Valorisation with Organic Rankine Cycle Technology in Energy Intensive Industries.* https://www.tasio-h2020.eu/.

Technology, T. (2012). *Energy Efficiency in Ceramics Processing: Practical Worksheets for Industry.*

TEEZ. (Regional Economic Development through indus-trial symbiosis, 2013). *Tyseley Environmental Enterprise Zone.* Tratto da https://www.energycapital.org.uk/tyseley-energy-park/

Terblanche, P., Kearney, M., Hearn, C., & Knights, P. (2018). Technology selection and sizing of on-board energy recovery systems to reduce fuel consumption of diesel-electric mine haul trucks. In *Energy Efficiency in the Minerals Industry* (p. 301-333). Springer Cham.

THERELEXPRO. (RFSR – CT – 2013 – 00029; 1/07/2013 – 30/06/2016). *Thermoelectric Heat Recovery from Low Temperature Exhaust of Steel Process.*

Todoschuk, T., Giroux, L., & Ng, K. (2016). Developments of Biocarbon for Canadian Steel Production Developments of Biocarbon for Canadian Steel Production; Canadian Carbonization Research Association:. *Hamilton, ON, Canada, 2016*.

TOREtech. (2019). *TOREtech-Energy efficiency in brick production.* Tratto da https://www.energy-innovation-austria.at/article/toretech-2/?lang=en

TotOptLis. (RFSR-CT-2010-00003-01/07/2010-31/12/2013). *Multi-criteria through-process optimisation of liquid steelmaking.*

TRANSECOTEH. (Structural funds; 01/09/2016–31/01/2020). *Promotion of eco-efficient non-conventional technologies for the recovery of useful metals from industrial waste by establishing partnerships for knowledge transfer with companies*. Tratto da www.imnr.ro/transecoteh

TRIS. (INTERREG EUROPE, 2016-2021). *Transition Regions towards Industrial Symbiosis.* Tratto da https://www.interregeurope.eu/tris/

Tsakiridis, P., Papadimitriou, G., Tsivilis, S., & Koroneos, C. (2008). Utilization of steel slag for portland cement clinker pro-duction. *J. Hazard. Mater. , 152*, 805-811.

U.S. Energy Information Administration. (2019). *International Energy Outlook 2019.* Tratto da https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf

UBIS. (EUROPEAN REGIONAL DEVELOPMENT FUND, 2017-2019). *Urban Baltic Industrial Symbiosis.* Tratto da https://ubis.nu/industrial-symbiosis-sites

UK Governemnt. (2014). Automated Module to pack Pilot Line for Industrial Innovation.

UNEP, I. I. (2008). *Green Jobs: Towards Decent Work in a Sustainable, Low-Carbon World .* Tratto da http://www.ilo.org/wcmsp5/groups/public/---dgreports/---dcomm/documents/publication/wcms_098504.pdf

Unilever. (2020). *how-we-create-value.* Tratto da www.unilever.com: https://www.unilever.com/Images/unilever-how-we-create-value_tcm244-548537_1_en.pdf

United Nations. (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development; A/RES/70/1.* New York, NY, USA: United Nations.

URIOM. (RCFS-CT- 2007-00010, 01/07/2007-31/12/2010). *Upgrading and utilisation of residual iron oxide materials for hot metal production.*

Vadenbo, C. B. (2013). Life cycle assessment model for the use of alternative resources. *Journal of Industrial Ecology, 17*, 363-374.

VALORISH. (Horizon Europe; 01/05/2024-31/10/2027). *Green VALORisation cascade approach of fISH waste and by-products through fermentation towards a zero-waste future.* https://cordis.europa.eu/project/id/101135078.

VALUES. (Valencian Innovation Agency & European Union through the Operational Program of the European Regional Devel-opment Fund (ERDF) of the Valencian Community; 2014-2020). *Recovery of waste for its use as secondary raw materials*. Tratto da https://www.itc.uji.es/en/itc-aice-potencia-la-valorizacion-de-residuospara-utilizarlos-como-recursos/

Varga, T., Bokányi, L., & Török, T. (2016). On the aqueous recovery of zinc from dust and slags of the iron and steel production technologies. *Int. J. Metall. Mater. Eng.* , 2.

Vladimirova, D. K. (2018). *SCALER: Lessons learnt and best practices for enhancing indus-trial symbiosis in the process industry.* Brussels, Belgium .

VUB-IES, 2. (2018). *A Bridge Towards a Carbon Neutral Europe.* Europe's Energy Intensive Industries contribution to the EU Strategy for long-term EU greenhouse gas emissions reductions, Vrije Universiteit Brussel (VUB) and Institute for European Studies (IES).

Wang, R. R., Zhao, Y. Q., Babich, A., Senk, D., & Fan, X. Y. (2021). Hydrogen direct reduction (H-DR) in steel industry—An overview of challenges and opportunities. *Journal of Cleaner Production*, 129797.

Waste sludge incinerator using pyrolysis and gasification, and relative process ; us2016245508 (a1). (s.d.). Tratto da https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2015049659

WaterWatt. (G.A. 695820; 1/4/16-31/3/19). *Improvement of energy efficiency in industrial water circuits using gamification for online self-assessment, benchmarking and economic decision support.*

WaterWatt. (H2020 G. A. No 695820; 2016-2019). *Improvement of energy efficiency in industrial water circuits using gamification for online self-assessment, benchmarking and economic support.*

WBCSD/CSI, W. B. (2009). *The Cement Sustainability Initiative: Cement Industry Energy and CO2 Performance, Getting the Numbers Right.*

WEEE Forum, 2. (2019). *Internation e-waste day, https://weee-forum.org/iewd-about/.*

WHAM. (G.A. No. 800654 01/09/2018-28/02/2022). *Water and related energy Hub Advanced Management steelworks.*

Widmer et al. (2005). *"Global perspectives on e-waste".* Environmental Impact Assessment Review, 25, 436-458.

Willard, J., Jia, X., Xu, S., Steinbach, M., & Ku, V. (2021). Integrating Scientific Knowledge with Machine Learning for Engineering and Environmental Systems.

WINCER. (2015-2017). *ECO/13/630426/WINCER PROGRAMME: CIP-EIP-Eco-Innovation-2013 CONTRACT TYPE: CIP Eco-Innovation, WINCER WASTE SYNERGY IN THE PRODUCTION OF INNOVATIVE CERAMIC TILES.* Tratto da http://www.wincer-project.eu/

Wolff, A., Sonnenschein, D., Bialek, S., Stranziger, B., Schlimbach, J., & Hillmann , C. (June, 2019). Prediction of the temperature distribution in the hot blast stove with a switching Kalman filter. *METEC & 4th ESTAD.* Düsseldorf.

Won, J. K. (2006). Industrial symbiosis as an integrated business/environment management process: The case of Ulsan industrial complex. *Int. Forum Strateg. Technol.* , 423–428.

World Steel, A. (2014). *Energy Use in the Steel Industry.* Brussels, Belgium: World Steel Association.

Worldsteel. (s.d.). Tratto da www.worldsteel.org

Worldsteel. (2019). *Fact sheet: steel and raw materials.* Tratto da https://www.metsec.com/app/uploads/2020/02/worldsteel-fact-sheet.pdf

worldsteel. (2021, April). *Energy use in the steel industry.* Tratto da https://worldsteel.org/wp-content/uploads/Fact-sheet-Energy-use-in-the-steel-industry.pdf

Worldsteel. . (2021). *World steel in figures 2021.* Tratto da https://worldsteel.org/wp-content/uploads/2021-World-Steel-in-Figures.pdf

Wu, J., Lu, J., & Jin, R. (2021). Quantitative indicators for evolution of a typical iron and steel industrial symbiosis network. *Journal of Cleaner Production*, 125491.

Wu, J., Wang, R., Pu, G., & Qi, H. (2016). Integrated assessment of exergy, energy and carbon dioxide emissions in an iron and steel industrial network',. *Applied Energy, 183*, 430-444. doi:doi: 10.1016/j.apenergy.2016.08.192

Wu, M., Zhang, Y., Liu, G., Wu, Z., Yang, Y., & Sun, W. (2018). Experimental study on the performance of lime-based low carbon cementitious materials. *Constr. Build. Mater. , 168*, 780-793.

Wyns, T. K. (2018). *A Bridge towards a Carbon Neutral Europe (Commissioned Report). Vrije Universiteit Brussel (VUB) - Institute for European Studies (IES).* Tratto da https://www.glassallianceeurope.eu/images/para/industrial-value-chain-for-a-carbon-neutral-europe-sept-2018_file.pdf

Xianlai Zeng, J. L. (2014). Recycling of Spent Lithium-Ion Battery: A Critical Review. *Critical Reviews in Environmental Science and Technology, 44, 10*, .

Xiao, Z., Chen, M., Wu, S., Xie, J., Kong, D., Qiao, Z., & Niu, C. (2019). Moisture susceptibility evaluation of asphalt mixtures con-taining steel slag powder as filler. *Materials, 12*, 3211.

Yang, G. C., Chuang, T. N., & Huang, C. W. (2017). Achieving zero waste of municipal incinerator fly ash by melting in electric arc furnaces while steelmaking. *Waste Management, 62*, 160-168.

Yeung, L. H. (2013). Challenges in implementing green workforce development training. *PhD diss.* Massachusetts Institute of Technology.

Zhang Jiaxuan, C. S. (2018). *Comparison of combined cooling heating and power (CCHP) systems with different cooling models based on energetic, environmental and economic critweria.*

ZHYRON. (Horizon.2.4-Digital, Industry and Space; 01/01/2024-31/12/2026). *Valorisation of iron-rich & Zinc-containing steelmaking by-products via HYdrogen-based ReductiON.* https://cordis.europa.eu/project/id/101138276.

ZincVal. (RFCS; 01/10/2023-31/03/2027). *Valorisation of low zinc-containing residues.*

10 ANNEX I: Questionnaire

Technology Forecast SPIRE-SAIS

The main objective of Industrial Symbiosis is represented by the increase of production by saving energy and resources through the cooperation among companies that use by-products or waste from other companies. The use of underutilised resources, such as materials, energy, information, by one company or sector from another can provide competitive advantages for all participants, in terms of economic, environmental and social benefits. This concept can be promoted by several factors, such as saving resources, obtaining economic benefits, meeting environmental requirements (e.g. greenhouse gas emissions), scarcity of natural resources reduction as well as decreasing the waste amount going to landfills and incinerators.

The energy efficiency topic is also an important and crucial aspect that concerns not only energy cost saving, but also a more sustainable competitiveness. A reduction of the energy use or an improvement of the energy efficiency is vital not only from an environmental point of view, but also for the entire company, even for company with low energy costs as the reduced costs can have an impact on the profitability. Improved energy efficiency can provide a number of direct and indirect economic benefits such as increased competitiveness and higher productivity.

High energy-intensive industries, such as the chemical, cement, pulp and paper as well as steel and iron industries and refineries, represent a great potential for measures reducing in an efficient way the energy and resource consumptions.

This survey aims at gathering information to determine the current state of Industrial Symbiosis and Energy Efficiency in the European process industry. Please fill in all the questions since they are relevant for the research. However, you can skip some sections, if needed, but it will not take you long.

The survey will help to create the basis for obtaining a complete state of the art of implementing Industrial Symbiosis and Energy Efficiency in process industries.

At the end of the questionnaire, some general information about your company should be provided.

The data provided are protected by confidentiality and will be processed according to GDPR (General Data Protection Regulation). Data will remain within the consortium and will be published anonymously for statistical purposes only. Sending the survey, you give your consent for the data processing. You have the right to withdraw the consent in any time.

Section I Industrial Symbiosis

[a1] Does your company apply principles of the Industrial Symbiosis?*

Only one choice allowed

○ Yes fully.

○ Yes partially.

○ Not yet

Industrial Symbiosis not yet applied

[an1] My company is aware of the opportunities that Industrial Symbiosis represents for my sector.*

Only answer this question if the following conditions are met:
Answer was 'Not yet' at question [a1]' (Does your company apply principles of the Industrial Symbiosis?)

Only one choice allowed

○ I strongly disagree

○ I disagree

○ I neither agree nor disagree

○ I agree

○ I strongly agree

[an2] Which conditions/practices are the most important for the introduction/implementation of the Industrial Symbiosis practices?*

Only answer this question if the following conditions are met:
Answer was 'Not yet' at question [a1]' (Does your company apply principles of the Industrial Symbiosis?)

Please choose **all answers** that apply:

☐ Replacing raw materials with recycled materials from other sectors

☐ Providing by-products or waste to other sectors

☐ Building a network focused on Industrial Symbiosis and sustainability strategies with other sectors

☐ Sharing the same goals with other companies/sectors

☐ Green skills programs/measures/training for workforce

☐ Regulatory aspects/Legislation

[an3] Can You specify eventual further conditions/practices (namely different from the previously listed ones), which are important for the introduction/implementation of the Industrial Symbiosis practices?

Only answer this question if the following conditions are met:
Answer was 'Not yet' at question [a1] (Does your company apply principles of the Industrial Symbiosis?)

Please write your answer here:

Industrial Symbiosis applied

[ay1] What is the current level of Industrial Symbiosis in your Company?*

Only answer this question if the following conditions are met:
Answer was 'Yes fully.' *or* 'Yes partially.' at question [a1] (Does your company apply principles of the Industrial Symbiosis?)

Only one choice allowed

○ High

○ Medium

○ Low

Barriers & Strategy for IS

[a2] Is your company planning to apply principles of the Industrial Symbiosis more actively in the future?*

Please choose the appropriate response for each item:

Yes	Uncertain	No
○	○	○

[a3] Is your company planning to invest in a technology in order to implement or increase the level of the Industrial Symbiosis?*

Please choose the appropriate response for each item:

Yes	Uncertain	No
○	○	○

[a4] Please rate the main barriers eventually faced by your company in applying practices of Industrial Symbiosis (1=Not Important, 2=Less important, 3=Moderately important, 4=Important, 5=Very important)*

Please choose the appropriate response for each item:

	1	2	3	4	5
Insufficient information on the meaning of Industrial Symbiosis	○	○	○	○	○
Lack of skilled and qualified workforce	○	○	○	○	○
Specific skills gaps	○	○	○	○	○
Transversal skills gaps (e.g. green, digital, communication, etc.)	○	○	○	○	○
Company/sector culture	○	○	○	○	○
Working across different sectors	○	○	○	○	○
Cooperation challenge	○	○	○	○	○
Coordination challenge	○	○	○	○	○
Integration of regional stakeholders	○	○	○	○	○
Cost of investment	○	○	○	○	○
Outdated plants/ infrastructure/ equipment	○	○	○	○	○
Know-how protection (e.g. Patents, Intellectual property, Trade Marks, Copyright, etc.)	○	○	○	○	○
Lack of functioning and reliable networks/platforms (including legal questions and trust)	○	○	○	○	○
Geographical barriers	○	○	○	○	○
Regulatory issues (e.g. those related with end-of-waste criteria or the ETS Directive)	○	○	○	○	○

[a5] Can You indicate further barriers (namely different from the previously listed ones) faced by your company in applying practices of Industrial Symbiosis?

Please write your answer here:

[a6] Are you engaged in Industrial Symbiosis projects? Please, specify name, URL and their importance.

Please write your answer here:

[a7] Which are the main expected economical benefits from the application of the principles of Industrial Symbiosis?

Please choose **all answers** that apply:

☐ Increase of the competitiveness

☐ Increase of the sustainability

☐ Mutual cooperation, extension of business area

☐ Increase of the overall energy efficiency

☐ Reduction of the waste/disposal costs

☐ Creation of new business

☐ Generation of the revenues due to higher values of by-products and waste stream

☐ Costs sharing

☐ Other:

[a8] Which are the main expected environmental benefits from the application of the principles of Industrial Symbiosis?

Please choose **all answers** that apply:

☐ Reduction of by-products

☐ Reduction of wastes

☐ Reduction of natural resources exploitation

☐ Reduction of pollution (e.g. emissions reduction)

☐ Reduction of greenhouse gas emissions (e.g. CO2)

☐ Reduction of raw materials consumption

☐ Reduction of the overall ecological footprint on the planet

☐ Other:

[a9] Which are the main expected social benefits for your company from the application of the principles of Industrial Symbiosis?

Please choose **all answers** that apply:

☐ New jobs

☐ Improvement of work

☐ Workers performance

☐ Improved green skills of the existing workforce

☐ New professional figures

☐ Other:

[a10] Which are the main expected social benefits for your company's region from the application of the principles of Industrial Symbiosis?

Please choose **all answers** that apply:

☐ Existing jobs maintained

☐ New Jobs

☐ New professional figures

☐ Benefits to the present and future community

☐ Reduction of local environmental impact

☐ Other:

Section I Energy Efficiency

[b1] Does your company apply principles of the Energy Efficiency?*

Only one choice allowed

○ Yes fully

○ Yes partially

○ Not yet

Energy Efficiency not yet applied

[bn1] My company is aware of the opportunities that Energy Efficiency represents for my sector.*

Only answer this question if the following conditions are met:
Answer was 'Not yet' at question [b1] (Does your company apply principles of the Energy Efficiency?)

Only one choice allowed

○ I strongly disagree

○ I disagree

○ I neither agree nor disagree

○ I agree

○ I strongly agree

[bn2] Which conditions/practices are the most important for the introduction/implementation of the Energy Efficiency practices?*

Only answer this question if the following conditions are met:
Answer was 'Not yet' at question [b1] (Does your company apply principles of the Energy Efficiency?)

Please choose **all answers** that apply:

☐ Implementing energy efficiency initiatives in your overall business strategy

☐ Using energy management systems to track and optimize energy use

☐ Building a network focused on Energy Efficiency and sustainability strategies with other sectors

☐ Sharing the same goals with other companies/sectors

☐ Green skills programs/measures/training for workforce

☐ Regulatory aspects/Legislation

[bn3] Can You specify eventual further conditions/practices (namely different from the previously listed ones), which are important for the introduction/implementation of the Energy Efficiency practices?

Only answer this question if the following conditions are met:
Answer was 'Not yet' at question'[b1] (Does your company apply principles of the Energy Efficiency?)

Please write your answer here:

Energy Efficiency applied

[by1] What is the current level of Energy Efficiency in your Company?*

Only answer this question if the following conditions are met:

Answer was 'Yes fully' or 'Yes partially' at question [b1] (Does your company apply principles of the Energy Efficiency?)

Only one choice allowed

○ High

○ Medium

○ Low

Barriers & Strategy for EE

[b2] Is your company planning to apply principles of the Energy Efficiency more actively in the future?*

Please choose the appropriate response for each item:

Yes	Uncertain	No
○	○	○

[b3] Is your company planning to invest in a technology to implement or increase the level of the Energy Efficiency?*

Please choose the appropriate response for each item:

Yes	Uncertain	No
○	○	○

[b4]Please rate the main barriers eventually faced by your company in applying practices of Energy Efficiency (1=Not Important, 2=Less important, 3=Moderately important, 4=Important, 5=Very important)*

Please choose the appropriate response for each item:

	1	2	3	4	5
Lack of skilled and qualified workforce	○	○	○	○	○
Specific skills gaps	○	○	○	○	○
Transversal skills gaps (green, digital, communication..)	○	○	○	○	○
Company/sector culture	○	○	○	○	○
Working across different sectors	○	○	○	○	○
Cooperation challenge	○	○	○	○	○
Coordination challenge	○	○	○	○	○
Integration of regional stakeholders	○	○	○	○	○
Cost of investment	○	○	○	○	○
Outdated plants/ infrastructure/ equipment	○	○	○	○	○
Know-how protection (e.g. Patents, Intellectual property, Trade Marks, Copyright, etc.)	○	○	○	○	○

[b5] Can You indicate further barriers (namely different from the previously listed ones) faced by your company in applying practices of Energy Efficiency?

Please write your answer here:

[b6] Are you engaged in Energy Efficiency projects? Please, specify name, URL and their importance.

Please write your answer here:

[b7] Which are the main expected economical benefits from the application of the principles of Energy Efficiency?

Please choose **all answers** that apply:

☐ Increase of the competitiveness

☐ Increase of the sustainability

☐ Mutual cooperation, extension of business area

☐ Increase of the overall energy efficiency

☐ Reduction of the waste/disposal costs

☐ Creation of new business

☐ Generation of the revenues due to higher values of by-products and waste stream or to the lower cost of secondary raw materials

☐ Costs sharing

☐ Other:

[b8] Which are the main expected environmental benefits from the application of theprinciples of Energy Efficiency?

Please choose **all answers** that apply:

☐ Reduction of by-products

☐ Reduction of wastes

☐ Reduction of natural resources exploitation

☐ Reduction of pollution (e.g. emissions reduction)

☐ Reduction of greenhouse gas emissions (e.g. CO2)

☐ Reduction of raw materials consumption

☐ Reduction of the overall ecological footprint on the planet

☐ Other:

[b9] Which are the main expected social benefits for your company from the application of the principles of Energy Efficiency?

Please choose **all answers** that apply:

☐ New jobs

☐ Improvement of work

☐ Workers performance

☐ Improved green skills of the existing workforce

☐ New professional figures

☐ Other:

[b10] Which are the main expected social benefits for your company's region from the application of the principles of Energy Efficiency?

Please choose **all answers** that apply:

☐ Existing jobs maintained

☐ New Jobs

☐ New professional roles

☐ Benefits to the present and future community

☐ Reduction of local environmental impact

☐ Other:

Section II - Technical aspects

[ta1IS] If your company is involved in the application of Industrial Symbiosis practices, what resource synergies (in terms of improvement, reduction or exchange of material flows) are involved in or considered? Multiple choices are allowed.

Only answer this question if the following conditions are met:
Answer was 'Yes fully.' *or* 'Yes partially.' at question [a1] (Does your company apply principles of the Industrial Symbiosis?)

Please choose **all answers** that apply:

☐ Material flows

☐ Energy flows

☐ By products

☐ Waste

☐ Other:

[ta1EE] If your company is involved in the application of Energy Efficiency practices, what resource synergies (in terms of improvement, reduction or exchange of material flows) are involved in or considered? Multiple choices are allowed.

Only answer this question if the following conditions are met:
Answer was 'Yes fully.' *or* 'Yes partially.' at question [b1] (Does your company apply principles of the Energy Efficiency?)

Please choose **all answers** that apply:

☐ Material flows

☐ Energy flows

☐ By products

☐ Waste

☐ Other:

[ta2IS] If your company is involved in the application of Industrial Symbiosis practices, what main tools/technologies adopted for the implementation? Multiple choices are allowed.

Only answer this question if the following conditions are met:
Answer was 'Yes fully.' *or* 'Yes partially.' at question [a1] (Does your company apply principles of the Industrial Symbiosis?)

Please choose **all answers** that apply:

☐ Digital technologies

☐ ICT tools/technologies

☐ Process Technologies

☐ Technologies to improve the quality of by-products

☐ Other:

[ta2EE] If your company is involved in the application of Energy Efficiency practices, what main tools/technologies adopted for the implementation? Multiple choices are allowed.

Only answer this question if the following conditions are met:
Answer was 'Yes fully.' *or* 'Yes partially.' at question [b1] (Does your company apply principles of the Energy Efficiency?)

Please choose **all answers** that apply:

☐ ICT tools/technologies

☐ Process Technologies

☐ Technologies to improve the quality of by- products

☐ Other:

[ta3IS] If your company is involved in Industrial Symbiosis practices, who are the main actors involved (within your organization and external partners)?

Only answer this question if the following conditions are met:
Answer was 'Yes fully.' *or* 'Yes partially.' at question [a1] (Does your company apply principles of the Industrial Symbiosis?)

Please choose **all answers** that apply:

☐ Internal actors (e.g. Quality Manager, Energy Manager, ..)

☐ Industrial actors (e.g. other industries in various sectors, financial partners..)

☐ Public actors (e.g. public parties, local agencies..)

☐ Other:

[ta3EE] If your company is involved in Energy Efficiency practices, who are the main actors involved (within your organization and external partners)?

Only answer this question if the following conditions are met:
Answer was 'Yes fully.' *or* 'Yes partially.' at question [b1] (Does your company apply principles of the Energy Efficiency?)

Please choose **all answers** that apply:

☐ Internal actors (e.g. Quality Manager, Energy Manager, ..)

☐ Industrial actors (e.g. other industries in various sectors, financial partners..);

☐ Public actors (e.g. public parties, local agencies..)

☐ Other:

[ta4IS]In which area of your Company is the Industrial Symbiosis mostly applied? (multiple choices allowed)

Only answer this question if the following conditions are met:
Answer was 'Yes fully.' *or* 'Yes partially.' at question [a1] (Does your company apply principles of the Industrial Symbiosis?)

Please choose **all answers** that apply:

☐ Energy Department

☐ Environment Department

☐ Sustainability Department

☐ Production Process chain

☐ Maintenance

☐ Other:

[ta4EE] In which area of your Company is the Energy Efficiency mostly applied? (multiple choices allowed)

Only answer this question if the following conditions are met:
Answer was 'Yes fully.' *or* 'Yes partially.' at question [a1] (Does your company apply principles of the Energy Efficiency?)

Please choose **all answers** that apply:

☐ Energy Department

☐ Environment Department

☐ Sustainability Department

☐ Production Process chain

☐ Maintenance

☐ Other:

Section III Human Resources - Current and Future Workforce Organisation

[w1] Future Workforce Development: if your company is planning to apply Industrial Symbiosis/Energy Efficiency practices more actively or to introduce Industrial Symbiosis/Energy Efficiency practices in the future, how will it impact the size of your workforce in the next 3-5 years?*

Only answer this question if the following conditions are met:
Answer was 'Yes' at question [ay2] (Is your company planning to apply principles of the Industrial Symbiosis more actively in the future?) or Answer was 'Yes' at question [by2] (Is your company planning to apply principles of the Energy Efficiency more actively in the future?)

Please choose the appropriate response for each item:

	Yes	No
Do you plan to employ more people?	○	○
Do you plan to employ more women with respect to men?	○	○
Do you plan to employ more highly qualified people?	○	○

[w2] Can you specify further impacts (namely different from the previously listed ones) Industrial Symbiosis/Energy Efficiency practices on the size of the workforce in the next 3-5 years?

Only answer this question if the following conditions are met:
Answer was 'Yes' at question [ay2] (Is your company planning to apply principles of the Industrial Symbiosis more actively in the future?) or Answer was 'Yes' at question [by2] (Is your company planning to apply principles of the Energy Efficiency more actively in the future?)

Please write your answer here:

[w3] Which skills in Industrial Symbiosis / Energy Efficiency will needed to be updated most in the next 3-5 years? (answers in a scale from: 1 very high; 2 high; 3 moderate; 4 low; 5 no)*

Please choose the appropriate response for each item:

	1	2	3	4	5
Specific job related skills	○	○	○	○	○
Digital skills	○	○	○	○	○
Green skills	○	○	○	○	○
Social skills	○	○	○	○	○
Individual, personal skills	○	○	○	○	○
Methodological skills	○	○	○	○	○

[w4] What are the other specific and transversal skills needed concerning Industrial Symbiosis and Energy Efficiency?

Please write your answer here:

[w5] Are the following categories of employees aware of the needs of Industrial Symbiosis and/or Energy Efficiency competences in your company? Please indicate shares (in %) of those who are aware.

	Industrial Symbiosis	Energy Efficiency
Manager		
Employees		
Technicians		

[w6] Do you have personnel training programs on the topics of Industrial Symbiosis or Energy Efficiency?*

Please choose the appropriate response for each item:

	No specific programs	Training programs exist, but not yet implemented	Specific training programs implemented
Industrial Symbiosis	○	○	○
Energy Efficiency	○	○	○

[w7IS] Has at least one employee of your company participated in trainings that strengthened her/his skills or provided knowledge related to Industrial Symbiosis over the last 12 months?*

Only one choice allowed

○ Yes

○ No

○ I don't know

[w7ISy] Could you name some of the exact areas/topics addressed during these trainings? Please, specify.*

Only answer this question if the following conditions are met:
Answer was 'Yes' at question [w7IS]' (Has at least one employee of your company participated in trainings that strengthened her/his skills or provided knowledge related to Industrial Symbiosis over the last 12 months?)

Please write your answer here:

[w8IS] What kind of level of skills related to Industrial Symbiosis could you claim your employees have?*

Only one choice allowed

☐ I don’t know

☐ No level

☐ Low level

☐ Middle level

☐ High level

[w8ISy] How have your employees developed/acquired most of the skills related to Industrial Symbiosis?*

Only answer this question if the following conditions are met:
Answer was 'High level' or 'Middle level' at question [w8IS]' (What kind of level of skills related to Industrial Symbiosis could you claim your employees have?)

Please choose **all answers** that apply:

☐ During a formal VET process

☐ Through company level (non-formal) trainings

☐ Learned at work, while implementing daily tasks

☐ Other:

[w9EE] Has at least one employee of your company participated in trainings that strengthened her/his skills or provided knowledge related to Energy Efficiency over the last 12 months?*

Only one choice allowed

○ Yes

○ No

○ I don't know

[w9EEy] Could you name some of the exact areas/topics addressed during these trainings? Please, specify.*

Only answer this question if the following conditions are met:
Answer was 'Yes' at question [w9EE] (Has at least one employee of your company participated in trainings that strengthened her/his skills or provided knowledge related to Energy Efficiency over the last 12 months?)

Please write your answer here:

[w10EE] What kind of level of skills related to Energy Efficiency could you claim your employees have?*

Please choose **all answers** that apply:

☐ I don’t know

☐ No level

☐ Low level

☐ Middle level

☐ High level

[w10EEy] How have your employees developed/acquired most of the skills related to Energy Efficiency?*

Only answer this question if the following conditions are met:
Answer was 'High level' or 'Middle level' at question [w10EE]' (What kind of level of skills related to Energy Efficiency could you claim your employees have?)

Please choose **all answers** that apply:

☐ During a formal VET process

☐ Through company level (non-formal) trainings

☐ Learned at work, while implementing daily tasks

☐ Other:

[w11IS] Skills needs and how the company reacts to them: are you facing new skills demand because of Industrial Symbiosis for*

Please choose the appropriate response for each item:

	no	low	middle	high
Managers	○	○	○	○
Employees	○	○	○	○
Technicians	○	○	○	○

[w12ISm] How do you adjust the skills gaps of Managers concerning Industrial Symbiosis?

Please choose **all answers** that apply:

- ☐ Internal upskilling measures
- ☐ External training measures
- ☐ Recruiting new people
- ☐ Other:

[w12ISe] How do you adjust the skills gaps of Employees concerning Industrial Symbiosis?

Please choose **all answers** that apply:

- ☐ Internal upskilling measures
- ☐ External training measures
- ☐ Recruiting new people
- ☐ Other:

[w12ISt] How do you adjust the skills gaps of Technicians concerning Industrial Symbiosis?

Please choose **all answers** that apply:

- ☐ Internal upskilling measures
- ☐ External training measures
- ☐ Recruiting new people
- ☐ Other:

[w11EE] Skills needs and how the company reacts to them: are you facing new skills demand because of Energy Efficiency for*

Please choose the appropriate response for each item:

	no	low	middle	high
Managers	○	○	○	○
Employees	○	○	○	○

	no	low	middle	high
Technicians	○	○	○	○

[w12EEm] How do you adjust the skills gaps of Managers concerning Energy Efficiency?

Please choose **all answers** that apply:

☐ Internal upskilling measures

☐ External training measures

☐ Recruiting new people

☐ Other:

[w12EEe] How do you adjust the skills gaps of Employees concerning Energy Efficiency?

Please choose **all answers** that apply:

☐ Internal upskilling measures

☐ External training measures

☐ Recruiting new people

☐ Other:

[w12EEt] How do you adjust the skills gaps of Technicians concerning Energy Efficiency?

Please choose **all answers** that apply:

☐ Internal upskilling measures

☐ External training measures

☐ Recruiting new people

☐ Other:

General Information

[gi1] Do you want to give us the name of your company?*

Only one choice allowed

☐ No

☐ Yes: please name it here:

[gi2] Position of the person completing the questionnaire*

Please write your answer here:

[gi3]Country (to be chosen in the predefined list)*

Only one choice allowed

○ Albania

○ Andorra

○ Armenia

○ Austria

○ Azerbaigian

○ Belgium

○ Bosnia-Erzegovina

○ Bulgaria

○ Croatia

○ Cyprus

○ Czech Republic

○ Denmark

○ Estonia

○ Finland

○ France

○ Georgia

○ Germany

○ Greece

○ Hungary

○ Iceland

- Ireland
- Italy
- Latvia
- Liechtenstein
- Lithuania
- Luxemburgh
- Malta
- Republic of Moldova
- Monaco
- Montenegro
- Netherland
- North Macedonia
- Norway
- Poland
- Portugal
- Romania
- Russia
- San Marino
- Serbia
- Slovakia
- Slovenia
- Spagna
- Sweden
- Switzerland
- Turkey
- Ukrain
- United Kingdom
- Other

[gi4] Company size according to the number of the employees*

Only one choice allowed

- ○ SME
- ○ Medium Enterprise
- ○ Large Enterprise
- ○ Other

[gi5] Sector*

Please choose **all answers** that apply:

- ☐ Steel
- ☐ Minerals
- ☐ Non-ferrous Metals
- ☐ Engineering
- ☐ Chemicals
- ☐ Ceramics
- ☐ Cement
- ☐ Water
- ☐ Other:

[gi6] Type of product*

Please write your answer here:

Thank You for completing the questionnaire!

Submit your survey.

Thank You for completing this survey.