# SPIRE-CCNI 2050 Roadmap

**NOTE**

- This document is a **draft, and still fully in development**. This means that the **content of this document could still change**.
- **Investment estimates are incomplete, preliminary and not yet calibrated**

**Dated: 22 November**

**Draft for Stakeholder Consultation**

# Contents







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# Preface

**Document status:**

This document is a draft, and still fully in development. It has been produced in close cooperation with the seven SPIRE-CCNI working groups (chairs and co-chairs). The document is under significant time pressure, so these groups have not always seen the last changes, and the SPIRE-CCNI Core Team and Navigant have not fully reviewed this document. This means that the content of this document could still change. Following the stakeholder consultation, the gaps below will be addressed:

| Gap | Approach to fill in next version |
|---|---|
| **RDI Investments** | Not all investments have been estimated. Estimates are missing for several innovation programmes. These will be added in the next version and then a calibration of all investments will be completed. |
| **Deployment investments** | Investments for deployment of technologies are (in some cases) provided in the innovation programme. The total will be estimated (at a high aggregation level) for the next version. |
| **LCA/standards** | The need for standardised LCA methodologies and decision frameworks is stressed in multiple innovation programmes. This topic will be given more specific attention in the next version. |
| **Marble projects** | Example projects (marbles) will be added. |
| **Non-technological activities** | Non-technological activities will be described with more granularity. |

This draft provides a good basis for the stakeholder consultation; we are asking the stakeholders for input at a moment that we are still flexible to incorporate their insights.

With the interpretation of our findings, please take note of the following:

| Topic | Notes |
|---|---|
| **Investments in this document** | Preliminary investment estimates have been provided by the working group ([co]chairs), they will be calibrated between innovation programmes at a later stage.<br>Investment estimates may overlap with each other (for example, catalyst development requires substantial investment, but this is included in the advanced catalysts innovation programme and the CCU innovation programmes), and high-level estimates will be used for the next version to account for this.<br>Different principles have been applied in estimating the investments per innovation programme. For example, in some programmes, innovation is only included in the programme if it can reach TRL9 before 2050, in others a rolling programme approach is used to facilitate continuous evolution of technologies. |
| **Timeline** | The timeline will be critically reviewed later, so is subject to change. |
| **Assumptions** | This report builds on the assumption of "no greenhouse gas emissions electricity" in Europe in 2050. This is in line with the European Commission long-term strategy scenarios for 1.5°C.<br>Energy and carbon price assumptions are detailed in the annex of this document. |

**How to read this document?**

- The executive summary (chapter 1) still needs to be developed;
- Chapter 2 outlines SPIREs 2050 vision for the process industry and introduces SPIREs 3 ambitions;
- Chapter 3 describes the SPIRE innovation arena, presenting the innovation challenges for the process industry's transition towards zero greenhouse gas emissions and near-zero landfilling and near-zero water discharge in 2050 (paragraph 3.2), followed by the process industry's innovation needs, first at an aggregated level (paragraph 3.3), followed by sector specifics (paragraph 3.4). It continues detailing the concept of Hubs-4-Circularity (paragraph 3.5). The chapter closes of placing SPIRE-CCNI in the European Innovation Landscape;
- Chapter 4 presents SPIRE-CCNI's innovation areas, again first at an aggregated level (paragraph 4.1) and then for each innovation area separately (paragraphs 4.2 - 4.18); (much) more background, details and numbers on each of these can be found in the Annex (chapter 6; the correct pages can be reached with the hyperlinks in chapter 4).
- Chapter 5 adds it all up and comes to (for now preliminary) conclusions on the total required innovation investments.



**A.SPIRE** is the European Association which is committed to manage and implement the **SPIRE** (Sustainable Process Industry through Resource and Energy Efficiency) Public-Private Partnership. It represents innovative process industries, 20% of the total European manufacturing sector in employment and turnover, and more than 130 industrial and research process stakeholders from over a dozen countries spread throughout Europe. SPIRE brings together cement, ceramics, chemicals, engineering, minerals and ores, non-ferrous metals, steel and water sectors, several being world-leading sectors operating from Europe.

The mission of A.SPIRE is to ensure the development of enabling technologies and best practices along all the stages of large-scale existing value chain productions that will contribute to a resource efficient process industry.

SPIRE will likely transition to a new name under Horizon Europe. The final name has not been selected yet, and therefore in this document the preliminary name **SPIRE-CCNI** (Circular and Climate Neutral Industry) is used to refer to SPIRE under Horizon Europe.

# 1 Executive summary

*<<this will be developed after the stakeholder consultation>>*

# 2 SPIRE-CCNI 2050 vision

***Imagine Europe in 2050. We have near full employment, we enjoy living in clean cities, and we have managed to counter climate change. The process industry has made an unprecedented change. Through research and innovation, existing processes are significantly optimised, and new and disruptive processes have been developed and implemented. This enabled the process industry to drastically improve its environmental footprint and to realise a carbon neutral society, powered by "no greenhouse gas emissions energies" produced all around Europe. Products that once ended up on landfills are now recycled to become feedstocks for the process industry, through many regional hubs and contribute to a zero-waste and circular society. Technologies developed in Europe by and for the process industry over the past decades are being exported, boosting European GDP and maximising the global environmental benefits.***

## 2.1 Introduction

**Process industries are an essential part of the European economy.** Process industries are crucial components of numerous value chains that deliver goods and services to our society and to European citizens. The materials produced by the process industries ultimately aid in providing shelter and housing to families, transporting passengers or freight, offering comfortable working spaces, producing and preserving food and beverages, and producing the sophisticated devices needed in modern healthcare and high-tech digital world. In other words, process industries enable the life we are living. Process industries also create jobs (currently: 6.3 million directly and 19 million indirectly[1]), continuously attract talent, and incite academia to train the next generation of experts. Process industries contribute to GDP (€565 billion/year[2]), drive innovation, and develop solutions for societal problems.

**In the next decade(s), the European society must drastically change, adapting to constraints such as climate change, resource scarcity, and environmental threats.** Climate change is the preeminent issue of our time. The world is still far from being on track towards the objectives of the Paris Agreement. In a context of limited access to resources and urbanisation, our societies also need to transition quickly towards circular business models and practices. In Europe, the European Commission has an ambitious vision to cut $CO_2$ emissions by 50%-55% in 2030 and to have a carbon neutral and circular economy by 2050.[2] On the market demand side, citizens are increasingly requiring customised products, services, and solutions that are safe and do not harm the environment.

**Achieving these changes requires a transformation of the process industries as they operate on the intersection of energy and resources.** The energy sector will undergo a massive disruption along the energy value chain affecting all stakeholders in the next decades. This will result in a sustainable, highly digitalised, and dynamic energy system. The process industry will be part of this ecosystem and will improve and develop processes, in strong cooperation and alignment with the energy sector, to make optimal use of and contribute to the transition. The process industry is essential to enable a fast transition of the energy sector, as it can immediately take large quantities of green energy and green hydrogen necessary to reduce rapidly production costs at competitive level. Also, in the transition towards more recycled and bio-based materials, the process industry plays an important role as they can use these materials to partially replace primary resources.

**Value chains will evolve to meet new societal demands.** To meet the ambitious EU targets, an unprecedented wave of transformative innovation is needed. Value chains will become

[1] (SPIRE, 2018) Eurostat data and Cefic Analysis. VTT – A.SPIRE data group.
[2] (European Commission, 2018) 2050 long-term strategy "A Clean Planet for All"

circular and more complex, connected, and intertwined. Process industries will develop new activities, or cooperate (more) with existing players, both up and down the value chain. On the one hand, process industries will play a larger role in resource management, e.g., through recycling of resources, thereby creating new jobs and activities. On the other hand, process industries will work even more closely with brand owners and service providers downstream to ensure that the materials developed by the process industries are designed to fully fit into the circular economy without compromising on performance.

**Focused innovation efforts are needed to transform the European process industries.** The process industries will transform existing processes and develop disruptive new processes to fulfil the needs of this society in transition, both in the short and in the longer term. New solutions (both technical and non-technical) are needed. As major technological challenges are similar across process industries, increased collaboration is needed. Europe and its process industries can only succeed in solving the puzzles of climate change and circularity if they jointly define and implement ambitious research, innovation, industrial and financing policies enabling fast and smooth transitions.

## 2.2 Disruptive process innovations for improved environmental footprint of the process industry

**Through innovative solutions, the process industries will create value to society by advanced processes that produce new and even better materials. The process industry will produce and use the resources and energy carriers of the future efficiently.** Consumers will demand guaranteed quality, safety, performance, and sustainability (e.g., labour, environmental, and climate impacts) of the products and of the materials used. Product manufacturers and brand owners are increasingly sensitive to the environmental concerns of their customers and are rethinking product design across the entire value chain to adapt to society and regulatory demands. Through process innovation, the process industry will contribute to the improvement of the overall environmental footprint of products along the whole value chain (see Figure 1). To do so, the process industries will improve existing processes and develop disruptive new processes. The process industry will contribute to the development of new energy carriers, like hydrogen, ammonia, and methanol. Furthermore, due to the size of the process industry, it can boost the use of no-greenhouse-gas-emission-energy. At the same time the efficiency of energy use should be optimised. Resources will increasingly be recycled, strongly reducing the use of primary resources. Industrial $CO_2$ generation remaining in 2050 is of high purity, or purified, and can be reused effectively as a resource (Carbon Capture and Utilisation [CCU]). Excess $CO_2$ will need to be captured and stored in safe natural caverns.

While the focus of SPIRE-CCNI is on the process industry, the materials (for example plastic) it produces are converted by the manufacturing industry into products (for example plastic buckets). This is visualised in Figure 1. New and innovative materials can contribute to sustainability and circularity in many ways. SPIRE-CCNI will focus on minimising the environmental footprint of materials by:

- Producing innovative materials[3];
- Producing materials with a higher inherent recyclability.

[3] Materials produced by the process industry, enabling production of downstream products with improved functionality. Downstream products as such are not part of the SPIRE-CCNI focus.

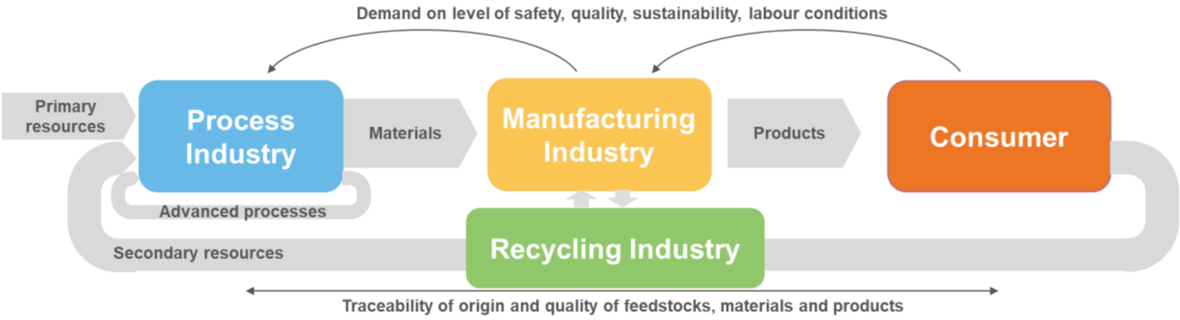


**Figure 1: The process industry uses primary and secondary resources to produce materials. Materials are transformed into products by the process industry. Consumer demand drives changes in process industries, like advanced process, increased use of secondary resources and innovative materials. Consumer demand also triggers improved traceability. The recycling industry (collectors, sorters and recyclers) will bring back secondary resources to both the process and the manufacturing industry.**

## 2.3 Resources of the future

**The upstream value chains will change as new resources become available.** The sourcing of raw materials for the process industry will change in type of resources and geographical location. As the economy becomes increasingly circular, more and more recycled products and resources will become available to replace primary resources. Additionally, a switch to low carbon footprint primary resources will occur, and carbon will be captured and used to make existing and new materials and products. Changing to new resources (coming from different locations) requires process innovation and a transformation of existing supply chains.

Next to biomass and waste, $CO_2$ is an alternative source of carbon available in Europe. Through advanced process technologies, $CO_2$ and CO captured and purified from industrial waste gases will be used to produce materials, polymers, and chemicals, including energy carriers with a lower environmental footprint than existing production routes. The implementation of $CO_2$-based production in the process industry will contribute to increased carbon circularity and decreased greenhouse gas (GHG) emissions in the process industries. The valorisation of $CO_2$ though power-to-X technologies will also provide solutions for renewable electricity storage. Excess of purified $CO_2$ should be stored adequately (CCS).

**The process industry will innovate processes to use more and more secondary resources.** In a fully circular and zero-waste society, all resources (including water) will be recycled, and a large share of resources will be recycled to the process industry.[4] However, primary resources will still be needed to cover part of the demand because it will not be technically feasible and/or economically viable to sperate all the waste streams to recycle back into materials. For certain streams there will be the need for primary resources due to quality and product specifications. Another reason that primary resources will still be needed is that for some materials the stock is expected to increase in the next decades. Secondary resources are mainly collected locally. Processing is done locally (e.g., for bulky materials to avoid transport of air), regionally when economies of scale are required, or over longer distances if that is economically feasible. Eco parks (where post-consumption materials will be collected) will be present locally and will allow the sorting and recycling of steel scrap, non-ferrous metals, ceramics, concrete, polymers/plastics, wood, and more. Additionally, new processes will be used to convert waste into usable resources. For instance, gasification of certain fractions of waste can be used to produce syngas. The industrial-urban symbiosis (IUS) will play an increasing role in connecting consumers with process industry by developing new technologies to, e.g., reuse waste and

[4] Recycling only occurs if more effective circularity strategies (e.g. reuse, repair, refurbish) are not possible

development of new business models. Urban mining and enhanced landfill mining will become extra drivers in the process towards secondary resources.

**Next to secondary resources, the role of bio-based resources will grow, asking for innovative and economically feasible processes.** Bio-based resources have an advantage compared to fossil resources, as their emissions from combustion are considered to be carbo-neutral[5]. If these are sequestered, it results in net negative emissions.[6] There are five main sources for bio-based resources that will be used by the process industries: wood-based biomass (e.g., trees), (agricultural) residues, functional crops (e.g., starch and sugar), waste, and wastewater. Wood-based biomass is produced and processed for material production in several European regions: the North, the South and especially the East, where biomass potential is high due to the availability of land and rural areas in the region. This can include pulp and paper and timber, but also more innovative materials and chemicals such as new textile fibres, aromatics, composites and hybrid materials. Agricultural residues and biogenic municipal solid waste are produced nearly everywhere. They can be used to generate biogas, which can be used as energy or resources. Functional crops, like sugar and starch, are used to produce bio-plastics, and vegetable oils for lubricants and personal care products. The recirculation from nitrogen and phosphates from wastewater treatment plants can significantly reduce the need for new mineral fertilisers. A restricting factor can be the availability of land to produce the bio-based resources. This land is also in demand for other applications, like energy crops and food. By applying technical and practical innovations, the yield per land area will be increased. There will be a need for regulation and certification systems to ensure the sustainability of the biomass.

**The process industry will innovate processes to produce and use hydrogen in the process industry in a sustainable way.** Hydrogen (when produced without GHG emissions) will replace fossil resources in the steel industry, will be used in the non-ferro metals industry for reduction of ores and will reduce the carbon footprint of many chemicals in which it is used as raw material and/or an energy carrier and will serve as a low carbon footprint fuel (100% hydrogen or mixed with an alternative energy source) in different industrial processes.

**New business models will be developed to enable the process industries to use resources of the future.** Most process industries rely on bulk transportation of resources. This can be a train full of iron ore or an oil tanker. For these commodities, there is a mature market with reliable supply. In a fully circular economy, new business models will take over as the direct streams from end of life products will deliver a supply that is less concentrated and more heterogenous. This is essential for the process industries to produce efficiently while increasing competitiveness. For instance, brokerage platforms for these resources need to be established based on innovative digital solutions. New business models should be developed that create fair benefits for all parties involved.

## 2.4 Energy of the future

**The European energy system is transforming to a climate-neutral context with less energy imports.** The EU aims to have 32% renewables in the energy consumption by 2030 (European Commission, 2018) and to have a fully climate neutral energy supply by 2050 (Leyden, 2019). At the same time, the EU's energy import will be massively reduced from 54% in 2018 to 20% in 2050. Energy will be produced more and more within Europe. By 2050, the share of electricity in final energy demand will at least double, bringing it up to 53%, and electricity production will increase substantially to achieve net-zero GHG emissions.

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[5] Combustion of bio-based resources only should occur if no other circularity strategy (which includes co-processing) can be applied to the material

[6] Note that this is only the case if both the biomass cultivation and the $CO_2$ storage occur within the same accounting scope

**To achieve its objectives the needs of electrical energy of the Process Industries will be substantially higher than today.** The process industry will use electrification of processes as a technology driver. For instance, heating of processes, now largely done by combustion of fossil fuels, will be replaced by electrically driven processes like heat pumps or direct electrical heating. Another example is electrochemical conversion, now used to produce some materials, and has potential for application in more process industries. Additional electricity will also be needed to produce green hydrogen for reprocessing $CO_2$ into materials and other power-to-X options. "No greenhouse gas emitting electricity" is needed to assure that this shift to electrical energy also results in an overall reduction of greenhouse gases.

**Large quantities of "no greenhouse gas emitting energy" will come from various sources and locations.** There are various possibilities to generate "no greenhouse gas emitting energy". Large scale availability of "no greenhouse gas emitting electricity" is crucial for the process industry to cut emissions rapidly. This will likely to a large extent be renewable electricity[7]. This is relevant, as for many technologies, the production of renewable electricity varies (for example with the speed of the wind), introducing a need for storage / demand side management.

Converting a small part of gas pipeline infrastructures in Europe would enable deployment of large production of green electricity captured, transported, and stored through a dedicated hydrogen pan-European pipeline. It would enable production of green hydrogen and electricity at scale necessary to transform the European process industries. Since gas infrastructure is less expensive than high voltage transmission lines, this route can be favourable, certainly on a shorter term.

Figure 3 shows that the process industry can play a key role in achieving synergies if regional supply of energy and resources is guaranteed. Note that the availability of these flows does not depend on the process industry. This picture represents one view of how Europe could work together to become energy independent.

**As the potential for "no greenhouse gas emitting energy" in Europe is restricted, process industries need to increase their energy efficiency.** European process industries have been working on energy efficiency for decades and transitioned successfully. Energy efficiency needs to be increased further as there might not be enough low carbon energy to make a fast transition. To achieve this, the process industries will need to improve existing processes and develop disruptive new processes. Digitalisation plays a key role in realising further energy savings. Especially in an increasingly complex system of energy and material flows, digital technologies can be used to optimise such systems rapidly. Energy efficiency can be increased further through optimisation on a larger scale beyond the scope of an individual company (e.g., waste heat exchange). In some cases, the process technologies required to meet the ambitions can be more energy intensive (e.g., for certain CCU applications). This additional energy demand should be delivered climate neutral.

**Process industries need to adapt to local conditions, using the available "no greenhouse gas emitting energy".** Not all industrial sites in Europe will have access to the same types and quantities of "no greenhouse gas emitting energy". Even the energy system design may differ between regions. As availability depends on regional aspects, a regional approach is required that also considers the developments over time. For instance, large supplies of wind energy from the North Sea will first become available to the industries in the coastal areas. Inland industries

[7] Wind power will account for over 50% of power generation. Offshore wind farms will generate power in the North Sea and Baltic Sea (Northern Europe and Scandinavia) and onshore large- and small-scale generation takes place throughout Europe. Regions with substantial solar irradiation will rely more on large-scale solar energy, accounting for 10%-30% of EU power generation.[7] For example, in Southern Europe (e.g., Spain, Italy, Greece) and Northern Africa (Morocco) there is opportunity for photovoltaic or concentrated solar power generation.

will depend on developments in energy transport, via high voltage transmission lines, gas, and other solutions. This best transport mode will depend on local characteristics of the energy system. The process industries also should adapt to the changing supply profile of electricity, using the available electricity from renewable generation at the time it is generated. Legislation and regulations can enable the cost effective introduction of renewable electricity in the process industry and the increase of renewable electricity generation capacity with a well-defined system of Guarantee's of Origin / Power Purchase Agreements.

**Energy will be supplied to process industries in different ways and local storage will increase flexibility.** Large volumes of hydrogen will be produced via low carbon hydrogen production routes located where conditions are favourable, usually close to power generation. Such hydrogen can be transported via pipeline or ship, in its regular form or in the form of ammonia or other hydrogen carriers. Power will be provided via high voltage power lines. Biomass can be supplied by train, ship, or truck. In some cases, it might be beneficial to work towards decentralised process industries located near renewable energy sources. This will create opportunities for decentralised small and medium sized industries. Local storage at process industry sites can serve as a buffer and allow for flexibility. Renewable energy deployment will rely on large scale production, transportation and storage of hydrogen and other energy carriers as ammonia.

## 2.5 Ambitions for the 2050 process industry

**Innovation will enable the European process industries to keep playing a pivotal role in a competitive, climate neutral, and circular European society.** SPIRE-CCNI is committed to delivering the necessary innovations. To guide the SPIRE-CCNI roadmap towards 2050, three ambitions have been defined:

| | |
|---|---|
| **Carbon Neutrality**<br>*Towards Net-Zero $CO_2$ emissions in 2050* | **Process industries will abate GHG emissions generated in their processes, both energy-related and process-related emissions to contribute to achieving a climate neutral society.** Process industries will develop the technologies to allow them to abate all their GHG emissions in a summed and combined effort of different Innovation programmes.<br>Many emission reduction options are available or under development. Impactful implementation depends on external conditions, like the availability of affordable renewable energy, and recycled or bio-based resources. The process industries will innovate their processes to make optimal use of these alternative resources, energy, and feedstock, once they are available. The achievement of a climate neutral society should align also with the goals to reach climate neutral regions across the EU. |
| **Circular Resources**<br>*Near-Zero landfilling and near-zero water discharge in 2050* | **Process industries will develop the required solutions to move towards near-zero-waste-to-landfill and near-zero water discharge in the EU.** Large volumes of secondary resources are being used by the process industries, but the goal is to recycle a larger share of European waste. Collaboration with the waste sector, manufacturers, and brand owners is key. The process industries will innovate processes to accommodate secondary resources and enable recycling for their produced materials, potentially with the need remaining for (temporary) safe storage of a very small fraction of hazardous materials.<br><< *where the rest of this document speaks about "zero-landfilling", this should be read as "Near-zero-landfilling"* >><br><br>The process industry will strive to reduce the water discharge to nearly zero. Although the process industry will focus on these two quantitative aspects, it is acknowledged that circularity covers more aspects, both qualitative and quantitative. |

| **Competitive Process Industries** *The innovations contribute to the EU's process industry's GVA grows quicker than the EU GDP* | **Process industries will deliver transformational innovation that will boost competitiveness.** The European Engineering industry will lead in the deployment and installation of sustainable production processes and will secure a great competitive advantage in the global scale-up that follows. The advanced processes will be more energy and resource efficient. They will deliver high quality materials produced sustainably in Europe and will provide a clear additional competitive advantage for the EU Process Industry. Advantage will happen in the context of a market and policy framework that will increasingly demand climate neutral and circular solutions. A circular economy is no longer dependent on imports of primary resources, decreasing sourcing risks and boosting the European economy. The independence for critical materials will improve, which will also have a positive effect on the trade balance. The same effect will occur with a switch to renewable energy generated in Europe. A strong arsenal of appropriate regulatory measures will be needed to support this transition to technologies with intrinsically higher costs to generate market uptake for climate and circular solutions. |
|---|---|

**SPIRE-CCNI is committed to transform the process industries by developing the required technologies to enable disruptive process innovation, as well as spearheading industrial symbiosis and digitalisation.** Figure 2 summarises SPIRE-CCNI's vision of how to achieve the required transformation of process industries. There are three transformation levers that are needed to go from the current process industries to the 2050 process industries: industrial-urban symbiosis, process innovation, digitalisation, and non-technological levers. Process innovation includes four technology drivers that help the process industries to reduce emissions and become circular: electrification, energy mix and hydrogen, capture and use of $CO_2$ and CO, and resources flexibility. Industrial symbiosis, digitalisation and the non-technological levers (e.g., new business models) support the transformation and embed the redesigned process industries in a circular and climate neutral society.

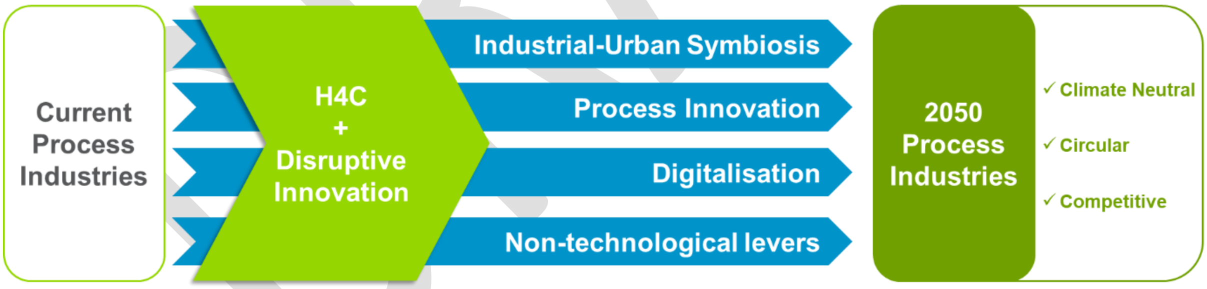


**Figure 2: Transformation levers and tools that will enable SPIRE-CCNI to achieve its ambitions**

**SPIRE-CCNI Partnership will be a key tool to accelerate innovation and drive collaboration.** Process industries will work together with the public sectors and other industries to maximise results through the development of disruptive and breakthrough[8] innovations and the creation of Hubs for Circularity (H4C). Working together with the power sector, for instance, to create local electricity storage or demand side management options. Or exchange of heat with the built environment. Process industries can also work together to exchange resources (e.g., between steel, cement and chemicals); industrial symbiosis and with the public sector (industrial-urban symbiosis). Industrial clusters will combine energy, materials and water in symbiotic

[8] Disruptive innovation is typically defined as innovation to target new markets or unmet needs. Breakthrough innovation is an innovation that results in commercial success. The missing piece of the puzzle that creates an attractive product or service.

business systems relying on the benefits obtained from exchanging the different flows from each other and profiting of proximity. Technologies such as CCU will enable new industrial hubs to be formed around existing large process plants.  Feed streams of CO2 and heat will enable new businesses to develop.

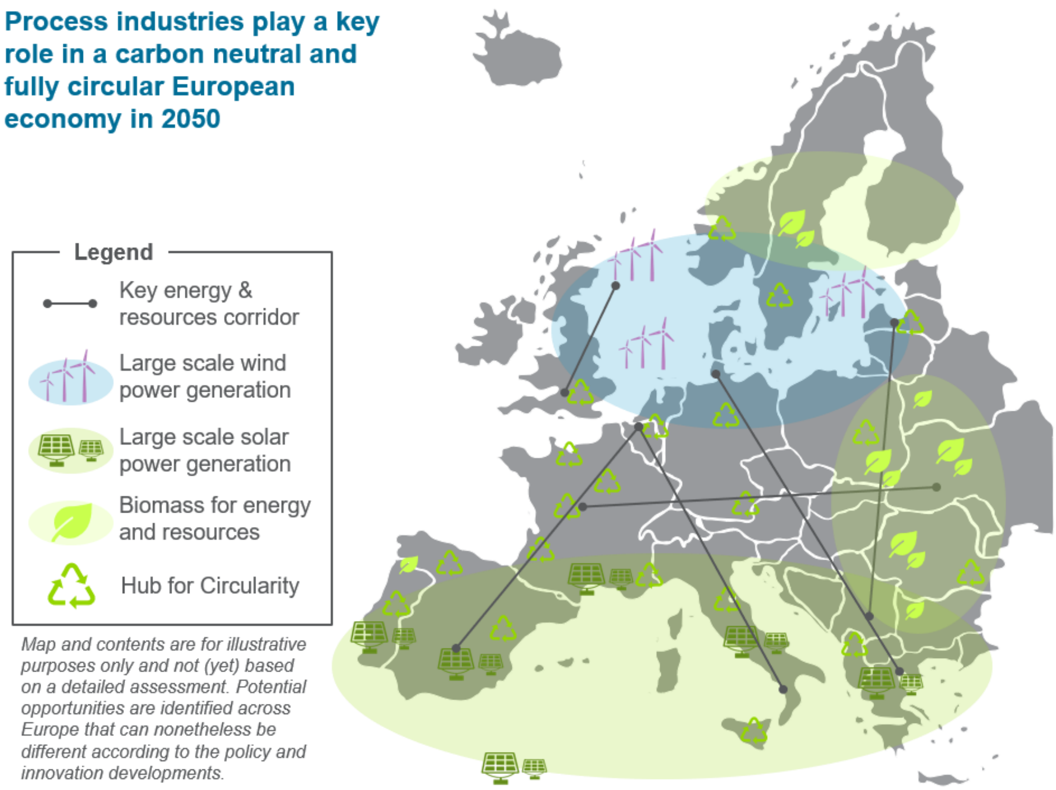


**Figure 3: EU Process Industry achieve synergies locally tailored to regional conditions (locations of the H4C are illustrative only – these have not yet been determined).**

# 3 SPIRE-CCNI's innovation landscape

## 3.1 Introduction

This chapter describes the landscape in which the SPIRE-CCNI sectors operate. Section 3.2 explores the challenge of the SPIRE-CCNI sectors in the context of climate change and waste. This forms the basis for the innovation needs, described in section 3.3 in general term. The sector-specific innovation areas are presented in section 3.4 for all SPIRE-CNNI sectors. Section 3.5 focusses on the cross-sectoral dimension by introducing the Hubs for Circularity. Finally, chapter 3.6 described how SPIRE-CCNI interacts with other stakeholders in the EU innovation landscape.

## 3.2 The innovation challenges for the SPIRE-CCNI sectors

This section explores the current position of the SPIRE-CCNI sectors related to GHG emissions and waste and highlights the overarching challenges.

### 3.2.1 Greenhouse gas emissions

The SPIRE-CCNI sectors collectively account for around 505 $MtCO_2$ of direct emissions in the EU, and 139 $MtCO_2$ of indirect emissions (see Figure 4). Together, this 644 $MtCO_2$ equates to about 15% of total EU emissions (i.e., 4,333 $MtCO_2$) (EEA, 2019). Electricity emissions are expected to decrease over time due to the decreasing GHG emissions in the electricity generation sector. The main challenge for reducing GHG emissions is in the direct emissions. Most direct emissions are related to fossil fuel combustion, but a share of emissions is also directly related to the process and is unavoidable.

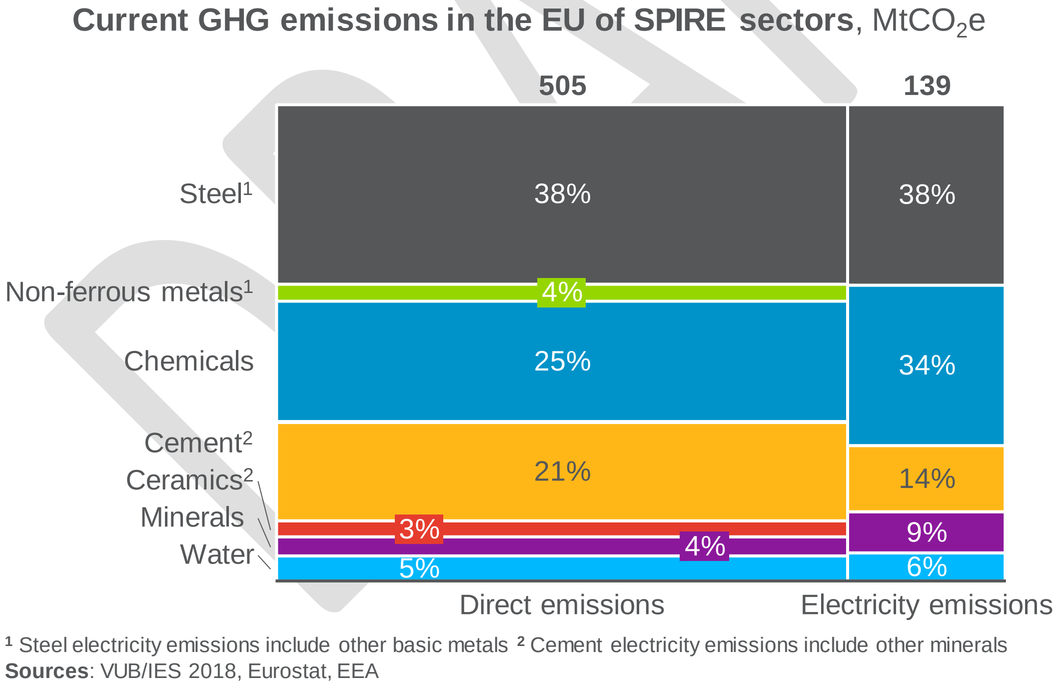


**Figure 4: Breakdown of current direct and electricity emissions of the SPIRE-CCNI sectors**

Besides the direct emissions and emissions from electricity generation, the process industries have an important downstream GHG emissions impact. For example, emissions may arise from downstream processing, or from end-of life treatment. On the other hand, products made from materials of the process industry can also avoid emissions downstream. For example, plastic foams used as insulation material in buildings can reduce energy consumption and associated emissions.

### 3.2.2 Waste

Waste is produced in different places in the value chain. There are problems with data quality when it comes to waste. Most data are available for end-of-life waste. Figure 5 shows World Bank data, but other data exists as well. However, it does show that construction waste is the largest category by volume, followed by municipal solid waste (MSW). Construction waste includes the materials produced by the ceramics, cement, and minerals sectors, but also metals (mainly steel). Of construction and demolition waste, 89% was recycled in the EU in 2016 (Eurostat, 2019).

MSW is more heterogeneous, containing materials produced by (for example) the chemicals and metals sectors. Different waste treatment options are used in different countries for MSW. Of MSW, 46% was recycled in 2016 (Eurostat, 2019). Hazardous waste is collected and treated separately. Some is reprocessed and some ends up on specialised hazardous waste landfills. Agricultural waste is largely organic and can be used to produce biogas or for other useful applications. Medical waste is not allowed to be recycled due to current regulations. E-waste is a small fraction in terms of volume but contains many valuable materials. For that reason, it is collected separately, disassembled, and recycled. Industrial waste is relatively small according to World Bank data. The chemical, mineral, and metals industries recovered two-thirds of their waste and disposed one-third (EEA, 2019).

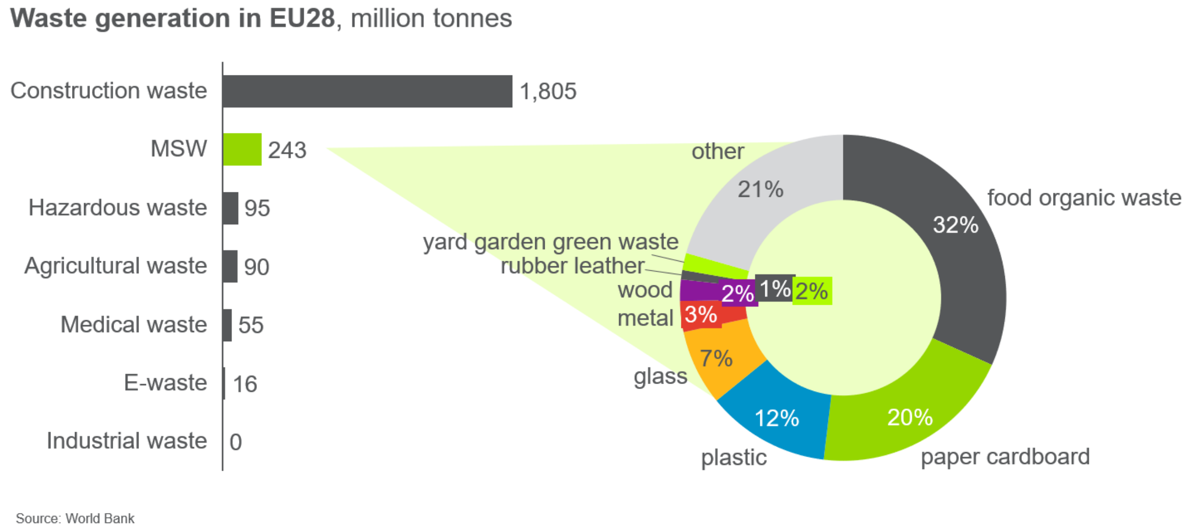


**Figure 5: Breakdown of EU end of life waste generation (World Bank, 2018)**

However, the end-of-life waste is only part of the bigger picture. Figure 6 illustrates the European materials flows. As many materials have long lifetimes (e.g., concrete and steel in buildings) there is a large in-use stock of materials. Recycling can also take place before the end of life, for example by reusing by-products of one sector as input for another.

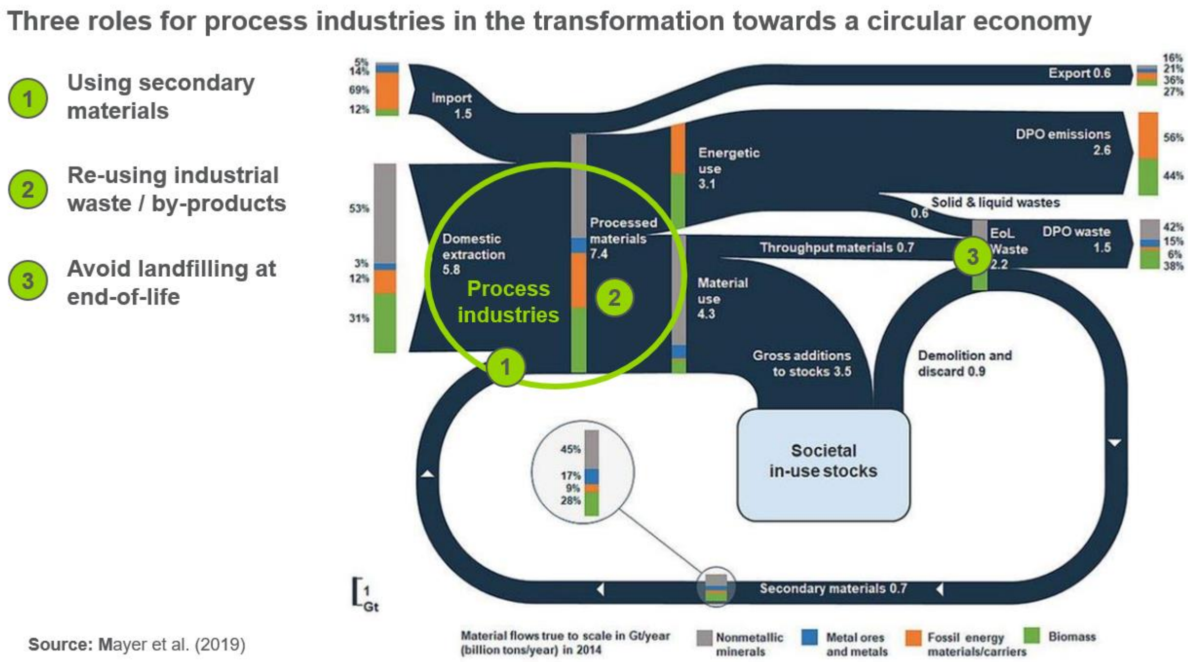


**Figure 6: Materials flows through the EU28 economy in 2014, and the roles of the process industry. Based on (Mayer, Haas, Wiedenhofer, Krausmann, & Blengini, 2019)**

The EU has set a number of targets on waste and circularity: recycling 65% of municipal waste by 2035, recycling 70% of packaging waste by 2030, reducing landfill to maximum of 10% of municipal waste by 2035, and 100% separate collection for hazardous household waste (by end 2022), bio-waste (by end 2023), and textiles (by end 2025). In its scoping study for the Circular Economy package, the European Commission focuses on metals, plastics, phosphorus, wood and paper, and agricultural products and waste. Rock and ceramics were not prioritised (European Commission, 2014).

SPIRE-CCNI sectors are active in the processing materials. They play a key role in using secondary materials, in reusing by-products and in ensuring that the materials they produce can be reused at the end of life instead of landfilled. To avoid landfilling their materials at the end of life, sectors need to cooperate with their downstream value chain. With changing processes, the by-products and the ratio inputs/outputs can change over time due to the implementation of new (low carbon) technologies. It is key to apply waste in the best possible way, ensuring that waste is used where it adds most value.

Sectors can work to develop circular business models (e.g., extending product life, product sharing platforms, or products as a service) to provide more functionality with their materials, reducing the material demand. Since that would not affect the production processes in the process industries, such demand reduction measures are not explicitly mentioned in this roadmap. These business models are better developed on an application-by-application level and are only within SPIRE-CCNI's scope if there are cross-sectorial elements.

## 3.3 Innovation needs

Figure 7 sketches a picture of what the process industry could look like in 2050, without GHG emissions and with steeply increased use of secondary resources (near-zero landfilling and discharge of wastewater), often after significant innovation.

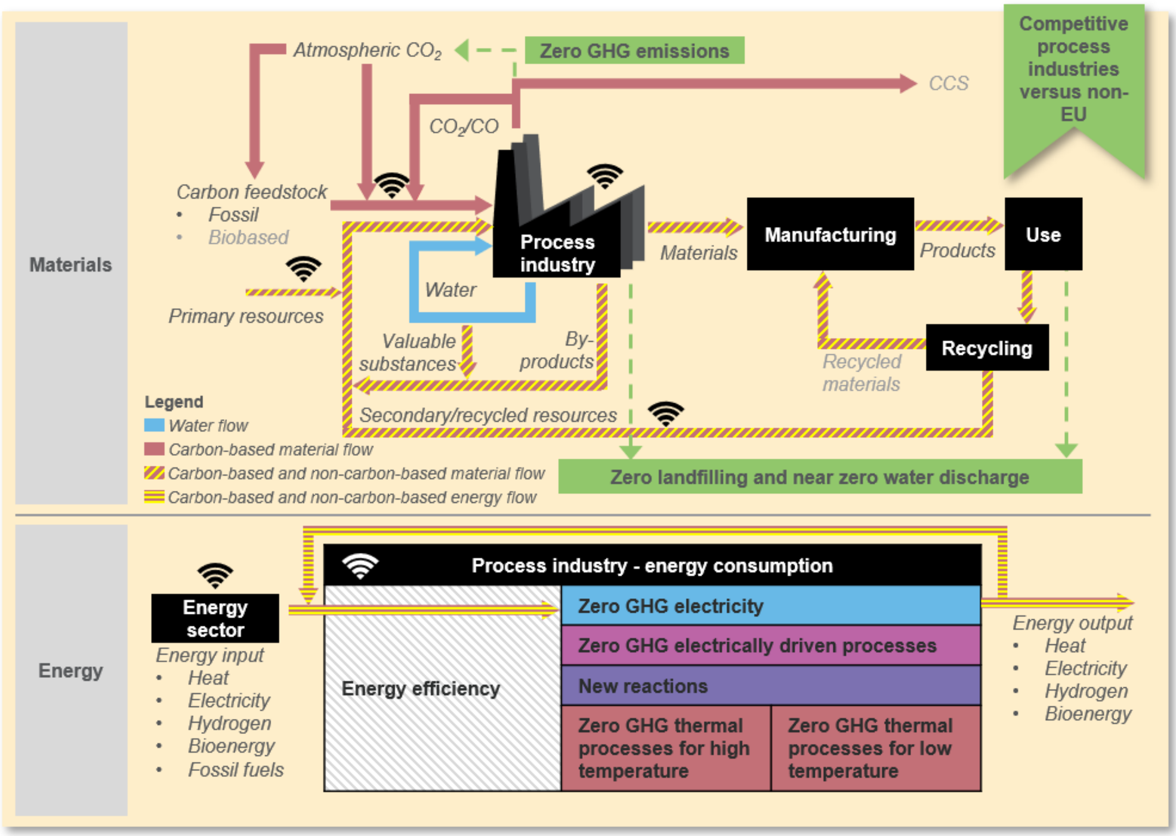


**Figure 7: Visualisation of the transformation of the process industries towards zero GHG emissions and near-zero landfilling and waste water discharge.**

The figure shows that the process industry delivers its materials to the manufacturing industry, which produces consumer products.

## 3.3.1 Secondary raw materials

After their use, some products can be mechanically recycled (which typically flows back into the manufacturing industry).

The other materials can be recycled by looping them as secondary raw materials into the process industry—or, to a limited extent, be incinerated (with energy recovery). With the multitude of sectors within SPIRE-CCNI, the many different processes within each sector (especially for the chemical industry), at different locations offering different local needs and opportunities for closing material loops, the challenge is to sort and separate all material flows, and to find technologies to recycle them back into the optimal processes.

These different processes also produce by-products/waste. For the range of by-products/waste for which no useful application exists, the challenge is again to find technologies that recycle them back into the optimal processes.

With the desire for near-zero wastewater discharge, the materials currently contained in the wastewater will at least partially be looped back into the process as secondary resource again, again requiring new processes to upgrade these.

Finally, $CO_2$ (and CO) capture and utilisation provides $CO_2$ as a (secondary) resource for carbon-based materials.

## 3.3.2 Primary resources

The strong increase of the use of secondary materials will be insufficient to cover for the process industry's full resource needs. Therefore, primary resources will still be needed. Bio-based resources will increasingly be used as primary resources, leading to new, often aqueous, processes. This poses new challenges for industrial processes. Virgin minerals, metal ores, and fossil feedstock will still be needed—the latter only to the extent that post-use emissions can be compensated for.

### 3.3.3 Water discharge

*<< to be added later >>*

### 3.3.4 $CO_2$ emissions

The new processes needed to process the changed resources will need to be developed, the starting point will be no emissions of GHGs, which can be achieved using similar principles as for the existing processes. For these:

- Electricity will be produced without GHG emissions in 2050. It might appear that emissions of current electricity use are automatically reduced to zero; however, this comes with the need to deal with fluctuations in the supply of electricity.
- **Energy efficiency** will reduce the size of the effort to reduce all other emissions significantly, often also improving the competitiveness of processes. A next generation of energy efficient technologies is to be delivered (like process intensification, enabled by 3D printing of process equipment, and new separation technologies), and to some extent also by applying technologies that just improve the energy efficiency by a couple percent.
- The **emergence of large-scale, cost-effective renewable electricity** also paves the way for electrification of many different reactions, avoiding the need for generating heat from fossil sources. The technologies required for this shift still need to be developed; integrated process routes converting renewable energy (for example solar radiation) directly into materials are being developed and combined using renewable energy with energy efficiency gains.
- **Hydrogen**, for which many new production routes which do not emit GHGs will be developed, will increasingly provide the energy input to drive reactions, which also enables many CCU processes.
- Remaining **thermal energy use** can be provided by electricity, for higher temperatures by developing electrical furnaces/kilns (which in some cases also generate process efficiency gains), and for lower temperatures with heat pumps (again leading to efficiency gains), flexible hybrid boilers (operating on renewable electricity when this is abundantly available), biogas, and/or geothermal energy.
- Most $CO_2$ currently generated is associated with energy supply and can be avoided using the options mentioned above. In some processes, however, $CO_2$ is formed as a by-product of the intended reaction (for example, $CO_2$ is generated as a by-product in the reactions forming cement and lime). The options to eliminate these process emissions are more limited, to CCU (on the longer term with permanent applications) and Carbon Capture and Storage (CCS).

*<< Other GHGs will be assessed after the stakeholder consultation>>*

## 3.4 Sector-specific status

This section presents sector-specific challenges and considerations for each of the sectors participating in SPIRE-CCNI. Often significant innovation is needed to harvest the potential mentioned in this section.

### 3.4.1 Cement

Although concrete products have a long-life time, the redevelopment of buildings and infrastructure creates large amounts of demolition waste (33% of total waste by mass in Europe). This material can be recycled to a high extent to avoid landfilling. Coarse particles can be **reused to replace virgin aggregates** in concrete if they have been re-carbonated to improve their strength. The fine fractions can be split into sand and a hardened cement-paste. The paste can be reused in cement or clinker production through direct substitution of raw materials or as an additive to cement.

The most energy-intensive step in cement-making is the production of clinker in a **kiln** where raw materials (limestone, shale or clay, and other materials) are **heated up to 1,450ºC**; 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.). The replacement reached 46% in 2017, of which 16%-point has a biogenic origin (CEMBUREAU, 2019). Technically, the amount of alternative fuels can be much higher, with some plants using more than 90%. On average, a share of alternative fuels of 60% is seen as achievable assuming availability. Electrification of cement kilns is technically an option and is being researched by the cement sector.

During this process, calcination occurs where $CO_2$ is released (**process emissions**) and then clinker is formed; as explained in Section 3.3, there are limited alternatives to abate these:

- The cement companies in Europe have started several research and demonstration projects. A cement specific option is calcium-looping, an absorption process in which calcium oxide is put into contact with the $CO_2$-containing combustion gas to produce calcium carbonate.
- The cement industry actively researches the opportunities of recarbonisation (adding $CO_2$ to the product) during the making of concrete products, during the lifetime of the concrete, and in recycling of concrete fines to cementitious materials.
- Cement companies in Europe have started several research and demonstration projects on a wide range of CCS/CCU technologies including pre-and post-combustion, oxyfuel, direct separation and calcium looping". They are also developing a range of new cements with lower carbon footprints.

### 3.4.2 Ceramics

The clay and minerals that are used to produce ceramics are primarily virgin resources, but (depending on the application) a share of **fired ceramics waste can be reprocessed** (Cerame-Unie, 2012). Other inert wastes such as glass waste can similarly be included in ceramics products (Ceramica, 2019). However, the amount of recycled product in new products is limited (to below 5%) so the quality of the product is not underminded (CEPS, Economisti Associati & Ecorys, 2017). Waste can also be used as energy source in the ceramics sector (Cerame-Unie, 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 fed back into the production process (Ceramica, 2019). In Italy, a major producer of ceramics, 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.

The remaining waste from the production process, and the ceramics after use, is used for external recycling (typically for road construction or as secondary aggregate) or is landfilled. Some ceramics applications can also be reused to extend their lifetime (rooftiles, for example). Upcycling of ceramics is not yet possible. In 2015, 70% of the required water in the Italian ceramics industry was **recycled wastewater** (Ceramica, 2019).

Existing options can technically mitigate most fossil fuel-related emissions. Fuel is combusted to obtain the **high temperature needed** for the processes (including sintering, but also drying processes). According to the sector's 2012 roadmap electrification is an option (particularly for large kilns), but not yet economically viable (Cerame-Unie, 2012). Besides electricity, bioenergy can be used to replace fossil fuels, as can renewable hydrogen could be used, although that requires new burners.

Most direct emissions are related to fossil fuel combustion, but a significant share also arises from the ceramics processes. These **process emissions** are projected to amount to 7 $MtCO_2$ in

2050 (European Commission, 2018). Remaining process emissions can only be mitigated using CCS or CCU. There is, however, substantial potential to further reduce the energy needed in the processes using radical or incremental innovations. Radical innovations include both process innovations (e.g., electric field assisted sintering techniques or vacuum drying) and product innovations (e.g., zero-energy coatings) (BEIS, 2017).

### 3.4.3 Chemicals

The chemical industries' feedstock is largely virgin fossil-based, with only a **few examples of chemical recycling at this stage**, and with varying but small estimates of the share of **bio-based feedstock**, for example, 3% of total organic and inorganic feedstock (JRC, Insights into the European market for bio-based chemicals, 2013) and 10% of total organic feedstock (JRC, A global view of bio-based industries: benchmarking and monitoring their economic importance and future developments, 2016) (Accenture, 2017).

In 2018, in Europe (including Turkey), 11 million tonnes (26%) of plastic waste was **recycled**, 14 Mton (33%) was used for energy recovery, and 13 Mton (31%) was sent to managed landfill, with 4 million tonnes (10%) improperly disposed/leaked (Conversio, October 2019). This corresponds well with the Plastics Europe data (Plastics Europe, 2019), which indicates that 61.8 million tonnes of plastics has been produced in the EU in 2018, and 29.1 million tonnes plastic post-consumer waste has been collected,[9] of which 33% of collected plastic waste was recycled, 43% went to energy recovery, and 25% went to landfill. In the remainder of this document, we use the Plastics Europe data (as it covers the EU more exactly), noting that around 10% of waste is not collected—a challenge to be tackled with a combination of policy, behaviour change, and innovation.

The chemical industry is heterogeneous, with many different production processes. Nevertheless, a few processes emit most of the GHGs, and consume by far most of the feedstock (as the resulting products are used as feedstock for other (downstream) processes): ethylene plants (producing ethylene and propylene and other high value chemicals), ammonia plants and plants to produce other key building chemical building blocks

- Ethylene plants use **furnaces** to crack feedstock at high temperature (>800°C), producing amongst others ethylene, propylene, butadiene (and other $C_4$ molecules) and benzene (and other aromatics); there is a wide variety of options available to reduce their emissions:
  - Regarding feedstock: CCU-based options to generate hydrocarbons, replacing the fossil virgin feed of ethylene plants by bio-naphtha or by chemically recycled feed
  - Regarding energy resources for furnaces: replacing fossil fuels by bio-based or waste-based fuels and replacing existing furnaces by electrical furnaces
  - Address remaining emissions by application of CCS
- Ammonia production is based on **hydrogen**, which can be generated in many alternative manners—as will be described in Innovation Programme, "Alternative routes for the production of hydrogen," later in the report

Other relevant processes are:

- Chlorine production is already based on **electricity**; the shift towards "no greenhouse gas emitting" electricity will (almost) completely eliminate the greenhouse gas emissions;
- Methanol can currently be produced from **syngas** (a mixture of hydrogen and CO), which is produced from natural gas; for the future, there is a large variety of options available (after innovation), including methanol production using CCU (combining $CO_2$ and green hydrogen), electrochemical conversion, from waste gasification, and from biomass.

The chemical industry produces numerous other chemicals in numerous different processes, for which a wide variety of other innovative GHG emission reduction measures are available and will be described in the rest of the report.

[9] The difference between the production and the collected waste is not just not-collected waste but includes factors such as the lifetime of plastics and export as well. The Plastics Europe data is based on Conversio Market & Strategy GmbH data.

### 3.4.4 Non-ferrous metals

Non-ferrous metal production is electricity intensive, 58% of the energy input is in the form of electricity (69 TWh). Natural gas accounts for another 35% and the balance is for oil products, solid fossil fuels, and others (IES/VUB, 2019).

Non-ferro metals, like aluminium, copper, nickel and cadmium are used in a diverse range of applications and sectors. They used in transport (29%) and followed by construction (24%) and industry (19%). Packaging (11%), batteries (11%), and durables (5%) complete the list (Eurometaux, Not dated). The **end-of-life metals recovery rate** is in many of these sectors above 90%, except for packaging (60%) and electronic waste (<35%). The use of recovered metals is around 50% of the total non-ferrous material production. Metals do not lose their properties through recycling and can be reused repeatedly as pure metals and alloys. To achieve higher levels of metal recovery:

1. Innovations to allow for efficient and climate friendly recovery (including of metals in residues) and recycling of metals given that more and more difficult-to-recycle secondary resources (for example different types of aluminium alloys) will have to be processed in the future.
2. Large exports of scrap and products containing metals can be stopped, particularly to regions with poor recycling regimes, while setting up an infrastructure for new products, like EV batteries, solar panels, and wind turbines.
3. Improve the end-of-life recycling of vehicles.
4. Increase the recovery rates of WEEE.
5. Establish new value recycle value chains for value chains in which nonferrous metals have only recently been introduced (for example, the amount of aluminium in cars has been increasing).

***For copper:*** Secondary copper production can be more energy-intensive than primary production, depending on the quality of the scrap, and can lead to higher $CO_2$-emissions. Noteworthy, recycling coper from electronic waste can generate high $CO_2$-emissions due to the carbon in the waste. From a life cycle perspective, the carbon footprint of recycled copper is lower than from primary copper.

There is a theoretical potential for the non-ferrous metals industry as a whole to reduce (direct and indirect) GHG emissions beyond 90% compared to 1990 levels (IES/VUB, 2019). However, the largest share will come from decreasing the GHG emissions of the power sector, which is outside the scope of SPIRE-CCNI. **Direct emissions** can be reduced by:

- Further innovations such as the use of inert anodes in aluminium production;
- Electrification of smelters (e.g., move to hydrometallurgical and electrified pyrometallurgical processes).
- Fuel-shifts to lower emitting or bio-based inputs.
- The use of non-carbon reducing agents in smelting.
- Higher efficiency in furnaces and better process management systems (including digitalisation).

The **process emissions** caused by PFC emissions from aluminium production have been nearly completely eliminated.

Improved industrial waste water treatment to remove or recover hazardous and precious materials.

### 3.4.5 Minerals

The IMA members produce annually 180 million tonnes of industrial minerals for EU-28, Turkey, and Norway. Its products are: calcium carbonate (PCC & GCC), dolomite, limestone, lime, bentonite, diatomite, talc, kaolin, plastic clay, sepiolite, andalusite, magnesite, silica sand, and borates. Recycling rates vary between 35% and 63%,[10] with an average of 50% (IMA Europe, 2018).

The sector itself **does not use many secondary inputs**, as recycling of minerals mainly depends on the recycling of its applications (such as glass). To enhance recycling, the sector needs to create synergies between the primary and secondary raw materials. To achieve zero-waste, the main challenge appears to be to increase the recycling rate of products in which industrial minerals are applied, and to increase the share of recycling at the same quality. To this end, the sector needs to create synergies between the primary and secondary raw materials. A third challenge is to reduce the amount of waste from the mining of minerals; the amount is currently unknown, as this also depends on the (definition of) use for the restauration. The amount of waste from the production process is unknown.

The majority of the GHG emissions originate from the lime sector:

- Around 30% of the lime sectors own emissions are fuel-related emissions (with electricity forming only around 5% of the total energy use), which can be reduced to a small extent by **energy efficiency** measures (although **lime kilns** are already relatively efficient) and with fuel switch measures (with CCUS), with electricity to heat kilns still requiring extensive R&D.
- The other 70% of the sectors own emissions are **process emissions** ($CO_2$ emitted during the process), for which CCUS appears the most logical/only solution with the current processes.

### 3.4.6 Steel

Steel is a material that consists almost completely of iron, with small shares of carbon and even smaller shares of other elements such as manganese and nickel. Today, steel is primarily made using two different technologies: the integrated steel plant and the electric arc furnace (EAF).

Integrated steel plants are used to make primary steel (i.e. virgin steel) mostly from iron ore, which is extracted from mines, and a small share of scrap steel. As iron ore – a compound made up of iron and oxygen – is found in nature, it is chemically a very stable compound. Iron is not alone in this respect – most metals from aluminium to uranium are found in nature bound to oxygen. In primary steelmaking, energy and carbon are used to separate iron from oxygen in a blast furnace, and in subsequent steps, the product is adjusted chemically and physically into the final desired form with characteristics such as strength, flexibility and corrosion tailored to the needs of the end user.

In contrast, in an electric arc furnace (EAF), scrap steel and/or scrap substitutes such as direct reduced iron (DRI) are melted using electrical energy, thus entirely replacing all of the steps up to and including the energy-intensive blast furnace. Similar to the integrated steel plant route, the liquid steel produced from the EAF is casted and then shaped or rolled into its final form.

In 2018, more than 167 mio t of liquid steel were produced in the EU. The primary steelmaking contributed by almost 98 mio. t (58%) and the scrap-EAF route by almost 70 mio. t (42%).

The steel industry has made significant improvements in energy and yield efficiency, reducing the greenhouse gas emission intensity of steel production during recent decades. Further technological innovation should lead to continued reductions in emissions intensity over the next decade. To accelerate the greenhouse gas emission reduction and align with the objectives of

[10] Bentonite: 35%, Calcium carbonate: 49%, Feldspar: 50%, Kaolin: 52%, Clay: 45%, Lime: 63%, Silica: 43%, Talc: 58%. In these numbers, recycling refers to any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes; this includes down-cycling and recovery from fly ash from waste incineration.

the Paris Agreement, the steel industry will have to transition to one or more low-emissions technology pathways (including break-through), by:

- Full efforts on further energy efficiency gains
- Application of renewable energy sources (renewable electricity, hydrogen, etc.)
- Cross sectoral coupling

Under Horizon 2020 the steel industry worked together with other energy intensive industry in cross sectorial topics and continue to do so. SPIRE and the initiative for a Partnership Clean Steel will align their R&D objectives and plans on a regular basis.

### 3.4.7 Water

The European water sector is already circular to a large extent. After use, water is either fed back into the fresh water reservoirs or recycled directly back into the water supply system (Ellen MacArthur Foundation, 2018). The uptake of water by industry in Europe is about 54% of the total uptake for human activities (EEA, 2018). However, little is data is available on water quality and use (WssTP, 2017). Sewage sludge, a by-product of water treatment, is mostly reused (mainly in agricultural applications or incinerated) and about 9% of the sewage sludge is landfilled (EurEau, 2017).

The EC identified phosphorus as a priority material for the circular economy (European Commission, 2014) . A key source of **secondary phosphorus** is sewage sludge. Phosphorus extraction from sewage sludge is attractive, but still not done at industrial scale (Accenture, 2017).

The GHG impact of the European water sector is driven by its **fuel consumption** and by the **process emissions from the water treatment**:

- Energy is consumed by the pumps, motors, blowers, mixers, and other equipment. These are mainly electricity-driven (and will be eliminated by the switch to zero GHG emission electricity), but onsite generators are often used to secure energy supply and enable water supply even during a blackout.
- Key process emissions result from:
  - **Methane** emissions, arising from wastewater under anaerobic conditions during transportation and processing of the wastewater; these can be mitigated effectively by:
    - Proper design and management of the wastewater collection and treatment facilities to avoid anaerobic conditions
    - An anaerobic digestion installation, producing biogas
  - **Nitrous oxide**, produced in biological nitrogen removal processes (IWA, 2018).

### 3.4.8 The Engineering sector's role in the transition

Although the engineering sector does not have a substantial waste or emissions impact, it is crucial to provide Europe with the technological solutions to the challenges of climate change, energy security, and green manufacturing. Engineering firms have two roles: implementing new technologies and developing new technologies. Europe has some of the best engineering firms and uses its engineering capabilities and knowledge to implement technologies within Europe, and also largely outside of Europe. Some engineering firms have their own patented technologies and invest in R&D initiatives to developing new technologies. These technologies are also exported around the world.

To remain competitive in the future, it is key for the engineering sector to be involved in developing next generation technologies. Some economies outside of Europe highly stimulate investments in emerging technologies such as hydrogen or electrification and favour their national engineering firms. As a result, the European engineering sector is at risk of losing competitive advantage on these key technologies.

Digital technologies will make a big difference in process industries, and engineering firms are well-positioned to develop digital tools and services. Additionally, there is an impact in the engineering process itself. Where currently optimisation is often done manually in engineering, in the future, digital solutions can get better results more efficiently. For example, when designing a water treatment facility, the design is done manually today to optimise within the available space and reduce concrete use. With digital technologies this can be done more efficiently and while considering more factors, such as the wiring that is used, or the electricity consumption during operation. Besides lowering environmental impact, it also reduces costs and boosts competitiveness.

The engineering sector is a provider of many jobs in the EU. Action is needed to make sure that the engineering sector has enough people to facilitate the energy transition. More talent is needed in the engineering sector, which can be achieved by showcasing impactful and attractive projects. Besides attracting new, well-educated talent, it is also key to train existing engineers to enable them to use state-of-the-art technologies and develop new disruptive solutions.

## 3.5 Hubs for circularity

Besides the sectoral dimension explained in the previous section, an important cross-sectoral and regional dimension to the outlined innovation challenges should be considered. Process industries are often clustered to provide benefits. Regional hubs can boost innovation by creating communities of local stakeholders and create potential integration synergies for process industries. That is why the implementation of Industrial-Urban Symbiosis and Circularity needs to take place predominantly in regions. Some EU regions have ambitious objectives like those of SPIRE-CCNI, for example "Climate neutral region" or "zero-waste region", and this can boost the regional development of Industrial-Urban Symbiosis and Circularity.

Collaboration and long-term commitments across the boundaries of individual organisations and dealing with wastes and by-products often fails because of numerous barriers between the companies, even when the technologies are available and could in principle be adapted and used. This is among others due to "fragmented" ownership, misaligned corporate interests, and lack of knowledge about the potential of symbiosis and circularity in regions.

A facilitator can support regions to address these barriers. The facilitator can be the linking pin between stakeholders (both within the region and on EU level), analyse regional potential for symbiosis, identify what is needed to realize this potential, and facilitate collaboration between actors.

To use these regional benefits and to deliver solutions that are tailored to the regional context, SPIRE-CCNI developed the concept of Hubs for Circularity. The concept is based on discussions with regions, where initial facilitation structures are already in place and have shown initial results.

### 3.5.1 Defining Hubs for Circularity

A **SPIRE-CCNI** "**Hub for Circularity**" is defined as:

> *a hub of industrial (large companies as well as SMEs) facilities connected to each other and/or public facilities within a given geographical area (regions, cities etc.), that collectively achieve a demonstrable level of circularity and carbon neutrality in their use of resources (including resources, energy and water) whilst boosting competitiveness of the EU Process Industry in the global arena and sustainable growth.*

Figure 8 details the key components and workings of a Hub for Circularity (H4C).

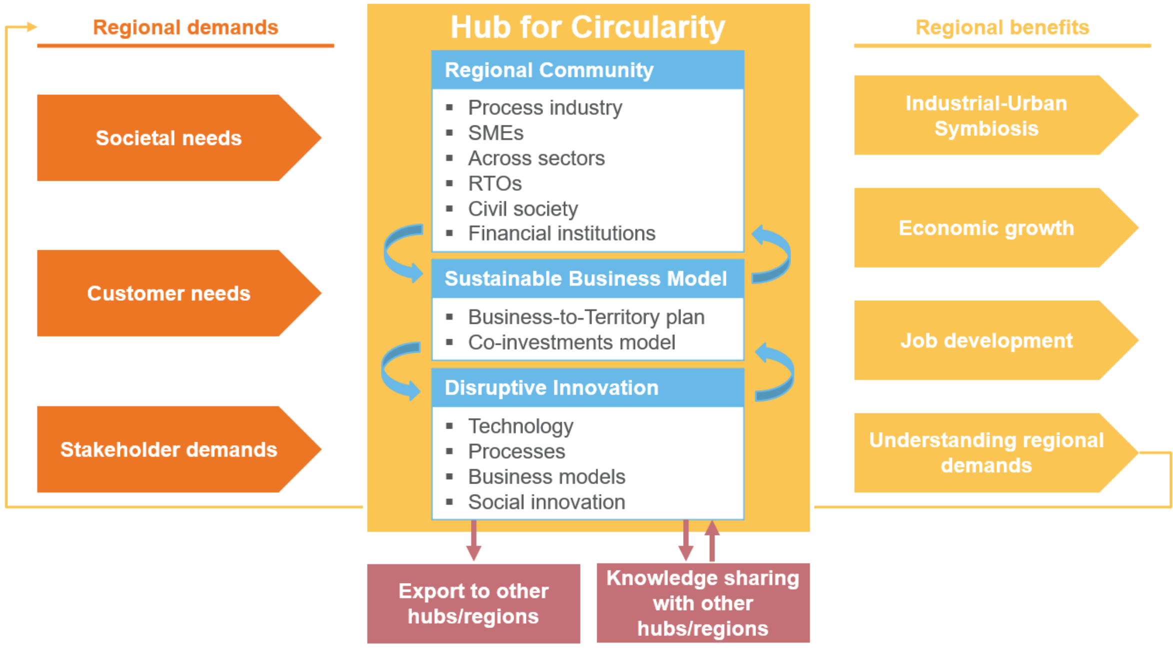


**Figure 8: Key components and working of a Hub for Circularity**

A H4C aims to deliver both regional and European benefits and address regional and European demands. Regional benefits are discussed in Section 3.5.2. Regional demands include societal needs such as circularity, environmental sustainability, and health, and stakeholder demands (including the needs of all public and private stakeholders in the regional community). Local networks will deliver products to the region itself as well as to more distant regions.

The H4C brings together a strong regional community that includes all stakeholders required to meet the regional demands: process industries and other sectors along novel value chains including small- and medium-sized enterprises (SMEs), research and technology organisations (RTOs), financial institutions, local authorities and civil society. The community, driven by the regionally present process industries, shares competences and resources and jointly identifies regional needs and opportunities. A circularity culture is developed to reduce GHG emissions and waste, and co-develop solutions. Industries become more open, trustful and committed to close collaboration within new business models.

The regional community has a sustainable operating model that facilitates continuous improvement of the region's performance and enables the H4C to adjust based on shifting needs. The business-to-territory (B2T) plan enables businesses to effectively turn collective problems and needs into advantageous and viable business models and opportunities. This delivers value to businesses and other stakeholders, triggering large scale deployment and co-investments from the various stakeholders.

With these ingredients, the H4C acts as an engine for mission-oriented radical and breakthrough innovation that bridges the "valley of death" and delivers impact. Due to the multi-stakeholder approach, the H4C can create the right conditionalities for the innovations to succeed (for example, innovative waste management infrastructure that enables industry to use waste as a feedstock, hydrogen infrastructure or electricity infrastructure). Besides technological and business model innovation, social innovation will increase the success rate of innovations (e.g., influencing customer behaviour to recycle, and redesign university curricula to adapt to new skill requirements.

Knowledge sharing takes place in a more coordinated fashion due to the facilitator, both within the H4C and between regions. Additionally, the H4C is connected to other relevant EU stakeholders or hubs. For example, the Living Labs in the water sector can be involved to co-create new industrial wastewater solutions, or digital initiatives can bring in specific expertise for sharing information across the value-chain. Geographical factors may require involvement of other stakeholders such as harbours.

Several examples exist today of emerging H4Cs: Kalundborg; Smart Delta Resources; trilateral region of North Rhine Westphalia (DE), Flanders (BE) and the Netherlands; Mo Industrial Park or South Norway Cluster.

Different regions present different challenges to meet the ambitions and different levels of development towards a hub-culture (mainly due to different presence of industries and geographical characteristics). Also, some regions already started facilitating activities towards symbiosis and circularity, whereas others are looking into fist possibilities. First conclusions signal, therefore, that there will be H4Cs at different maturity levels requiring specific support. They can be classified as in Figure 9.

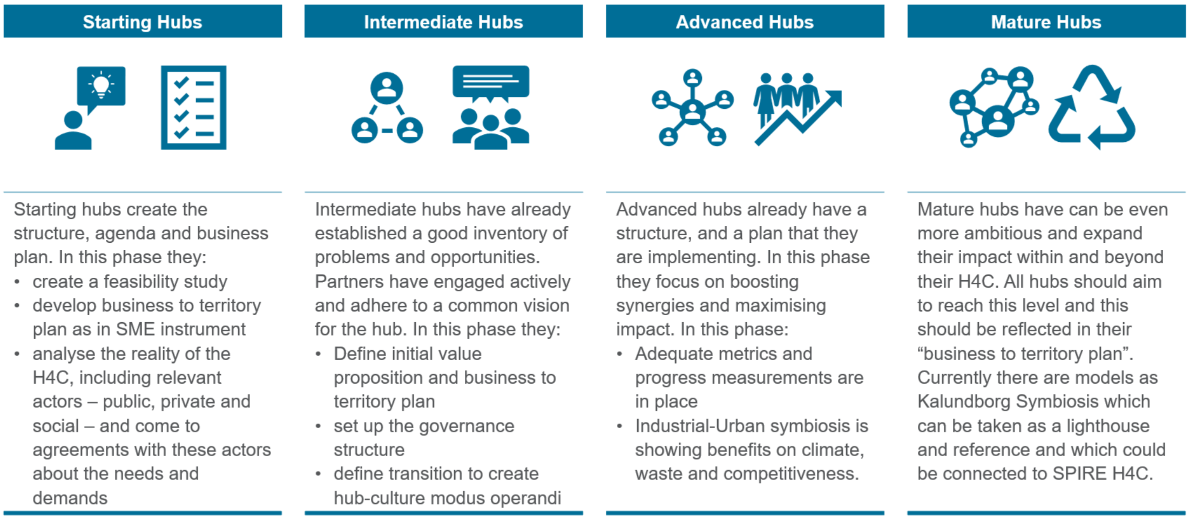


**Figure 9: Different maturity levels of Hubs for Circularity**

### 3.5.2 Benefits from H4C

The H4C provides numerous regional benefits:

- **Industrial-Urban Symbiosis:** Although the concept of industrial-urban symbiosis (I-US) has received plenty attention, there are several barriers that inhibit the successful implementation of this concept. The H4C are an effective vehicle to overcome the barriers and accelerate the transition towards a circular economy.
- **Economic growth:** Several mechanisms within a H4C boost economic growth in the region. First, the investments made in innovation and the required infrastructure or other economic activity. Second, the I-US results in efficiencies for process industries, water utilities, and other companies, which saves costs. Thirdly, the export of developed innovations brings additional revenue for the region. Finally, the hub will attract talent and investments due to the increased value of the region.
- **Job development:** The increase of economic activity translates directly into more work for local businesses (including SMEs). Indirect jobs are created due to the increased economic growth and the resulting snowball effect.
- **Understanding regional potentials:** As the H4C matures, the understanding of regional demands and potential synergies increases

These regional benefits can be achieved across Europe's regions. The large-scale application of the H4C concept enables regional communities to learn from other regions and increase their effectiveness and speed of closing energy and material loops.

### 3.5.3 Implementing H4C in SPIRE-CCNI

Long term commitment, support and investments from the European Union, Member States, regions, and industry are key to facilitate the H4C emergence and development, the installation of infrastructures and of the logistics needed to enable the B2T deployment. We suggest that:

- **The EC** supports the hubs by providing funds for their establishment or development depending on their maturity and B2T plan.
- **SPIRE-CCNI** supports the hubs by providing them access to resources, exchange of knowledge, training, and facilitation. SPIRE-CCNI also co-defines innovation priorities for funding together with the EC.
- **Regions** will participate in the definition and implementation of the B2T plan and co-invest in and provide the required infrastructures where necessary and possible.
- **Organisations that support regions** (ECNR, ERRIN, VANGUARD) will reach out and identify the regions that can become H4C. They also serve to connect to regions and create awareness of H4C.

The H4C is recommended be set up in regions with the following main characteristics:

1. A set of **specific needs and opportunities** related to economic and environmental transition. These can be goals on circularity (zero landfill waste; zero-water discharge), climate ($CO_2$ abatement) and a clear goal to create adequate returns out of new business opportunities thus generating growth and jobs through the transition (competitiveness). A special focus should be in regions which have the goals to become “zero-waste regions” and/or “climate neutral regions” by 2030, 2040, or 2050, depending on their point of departure. The front runners should move further, and the followers can become also exclusive in some new areas of recycling
2. A **concentration of process industry,** which is the only type of industry able to reintroduce bulk amounts of resources in the industrial process. Nevertheless, cooperation with other industries is desired (waste management industries, energy plants, and water utilities, et al.).
3. Sufficient **size of the region**. Regions with a large population or large economic activity that create a local demand for products are more likely to find synergies.

More details about how SPIRE-CCNI will support the H4C are presented in Section 4.14.

## 3.6 SPIRE-CCNI in the EU innovation landscape

*<< Will be added after the stakeholder consultation. Key messages:*

- *Next to SPIRE-CCNI, there are other PPPs, focussing specifically on, among others, the steel industry, the manufacturing industry, the bio-based industry, and hydrogen, and Water4All.*
- *Projects can tap into multiple sources of funding. >>*

# 4 SPIRE-CCNI's innovation areas

This chapter provides an overview of the portfolio of disruptive innovations that SPIRE-CCNI aims to achieve. At first, in Section 4.1, we present the overall overview of the innovation areas, after which Sections 4.2-4.18 describe each of the innovation areas. These sections contain hyperlinks to the Annex (Chapter 6), where more details about each of the innovation areas is given.

## 4.1 Innovation overview

Figure 10 and Figure 11 below provide an overview of the innovation areas summarised in this chapter, presenting how they deliver the future state shown in Figure 7 in Section 3.3. The remaining sections of this chapter detail what innovation is programmed for these innovation areas in the SPIRE-CCNI Roadmap – following the same flow as in Section 3.3.

- The innovation areas aiming at producing **innovative better recyclable materials** are described in Section 4.12;
- The innovation areas aiming at **increasing the use of secondary materials** are presented in Section 4.11 and, for Carbon Capture and Utilization, in Sections 4.8-4.10;
- **Valorisation of valuable substances in waste water** and preventing its discharge is presented in Section 4.11;
- The innovation areas increasing the **energy efficiency** are presented in Section 4.11; the innovation areas described in Sections 4.4-4.6 also lead to an increase of the energy efficiency;
- The innovation areas that **integrate increasing amounts of renewable electricity** are described in Sections 4.2, 4.3 and 4.6;
- The innovation areas associated with the alternative generation of **hydrogen**, its integration in the process industry and its storage are described in Section 4.7;
- The innovation areas aiming at **new technologies to deliver heat** are described in Sections 4.2, 4.3 and 4.5;
- The innovation areas strengthening **Industrial-Urban Symbiosis** and **Hubs for Circularity** are described in Sections 4.13 and 4.14;
- The innovation areas enabling many of the above through **digitalisation** are described in Sections 0 to 4.18.

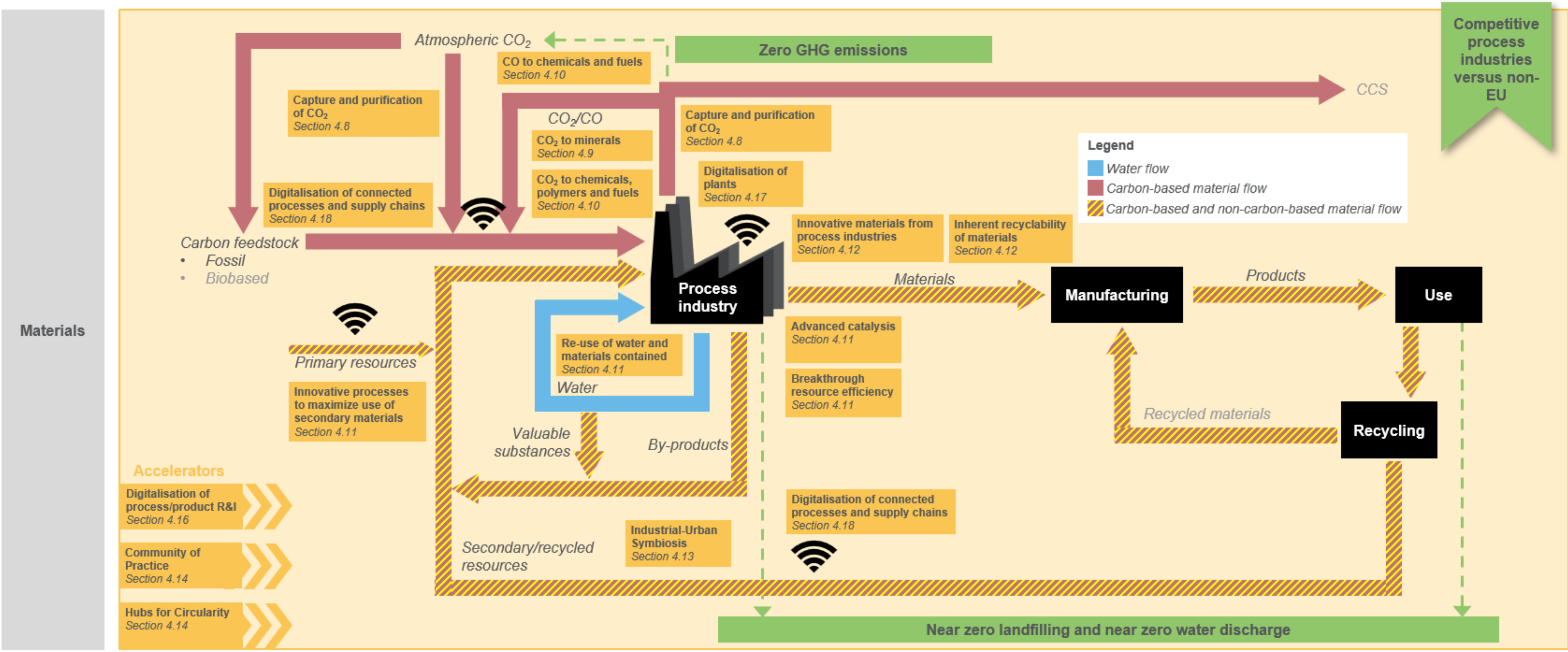


**Figure 10: Required innovation mapped to the 2050 material flows related to the process industry**

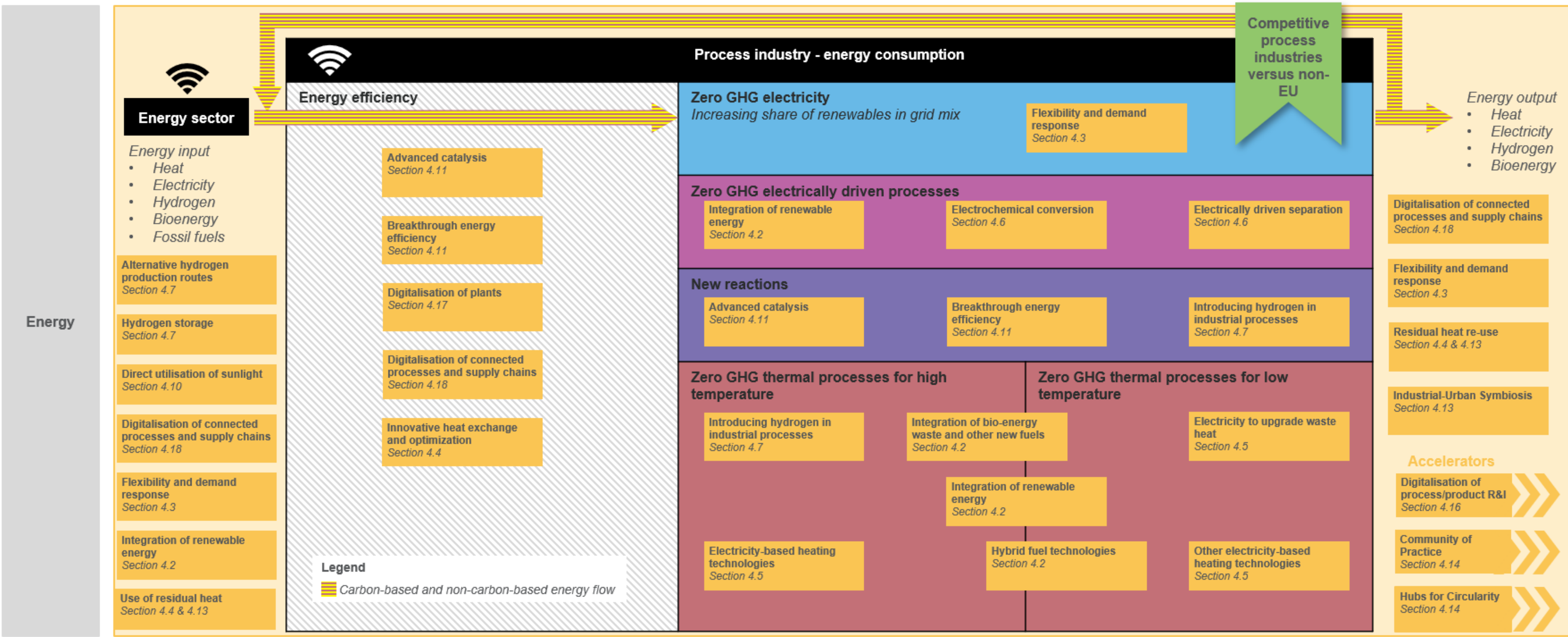


**Figure 11: Required innovation mapped to the 2050 energy demands of the process industry**

## 4.2 Integrating renewable energy carriers

European process industries will move from the current fuel mix, which is dominated by fossil fuels, to a fuel mix of various zero-GHG energy sources. Today's processes are tailored to the reliable supply of fossil fuels that are of constant quality and can easily be stored. If the renewable energy is already converted into another form of energy (e.g., electricity or hydrogen), the transition is straightforward because these issues are dealt with by the energy sector. However, directly integrating renewable energy generation with its use in the process industry can deliver higher overall efficiencies. The decreasing costs of several renewable energy options can also boost competitiveness.

**Integration of renewable energy**
*Section 6.1.1*

**Integration of renewables** such as solar heat, solar or wind power, and geothermal will require changes to the industrial processes due to different temperatures, supply profile, process control, storage, and more. To explore the extent of changes required and potential synergies, demonstration projects of various sizes are programmed before 2030 (e.g., PV powering a ceramics kiln, solar heat used for drying, or wind power for chlorine production).

**Integration of bio-energy waste and other new fuels**
*Section 6.1.2*

**Integration of bio-energy waste and other new fuels** requires adaptation of processes to different fuel characteristics (making the process biomass-tolerant) or pre-treatment of biomass to the requirements of industrial processes. These technologies are already under development and to be demonstrated before 2025, with more development to decrease costs afterwards.

**Hybrid fuel technologies**
*Section 6.1.3*

**Competitive hybrid transition to low-carbon industrial energy supply** is key. As several low-carbon fuels are expected to decrease in cost (e.g., hydrogen) or increase in volume (e.g., biogas) over time, hybrid systems that can quickly change from one energy source to another are essential to allow for a competitive transition and achieve more flexibility in the energy system. Hybrid modular systems are available and will be demonstrated at industrial scale. Integrated hybrid technologies will also be demonstrated.

For these innovations to be deployed at scale it is key that enough sustainable biomass is available at competitive costs, and that energy infrastructure allows for these developments. The innovation programmes in this innovation area collectively can contribute to several hundreds of $MtCO_2e$ GHG emission reductions.

## 4.3 Enhancing energy flexibility and diversity

The energy system of the future contains radically higher shares of variable electricity generation and as a result flexibility becomes increasingly important. The process industries are some of the largest energy consumers in Europe and a change in industrial energy demand can significantly affect the energy system. However, industrial processes are designed to run continuously at maximum capacity for economic reasons. The increased value of flexibility poses opportunities for the process industries (additional revenue streams) and enable a leaner energy system with lower societal costs.

**Flexibility and demand response**
*Section 6.2.1*

Process industries need to innovate to deliver **Flexibility and demand response**. Flexibility will be explored in existing processes, but also process redesign to facilitate flexibility is important (e.g., processes that can run faster or slower depending on the needs of the grid). Local storage of heat or electricity can provide a buffer that unlocks more flexibility potential, especially when integrated with the process. With these flexibility solutions, the rate at which the energy consumption can be increased or decreased (i.e., the response rate) is key. Most of the innovation will be realised before 2030.

To use the electricity in supply peaks even when demand is high, it is important that the transmission and distribution systems can transport the energy. Power market design should enable process industries to capture the value and boost their competitiveness.

## 4.4 Enhanced utilisation of different grades of heat

Heat is currently used in many industrial processes to drive material transformations. Although optimisation of heat management in process industries is not new, large flows of heat are still discarded. Using this heat for other industrial or non-industrial applications poses opportunities for reduction of energy consumption and increased competitiveness.

**Residual heat re-use**
*Section 6.3.1 & 6.12.1*

Heat use/exchange will be optimised across boundaries of the own plant/sector while using disruptive technologies to upgrade heat. Radical technologies to transfer heat from the process to other uses (e.g., thermoacoustic heat engines or plastic heat exchangers) enable this. Emerging technologies that efficiently convert lower-temperature heat into useful forms of energy are to be developed.

*<< to be further developed after the stakeholder consultation>>*

## 4.5 Electrification of heating and cooling processes

**Electricity to upgrade waste heat**
*Section 6.4.1*

A large part of the European process industries' GHG emissions originate from the use of fossil fuels for heating purposes. As temperatures grow to around 150°C, this heat can now be delivered by **heat pumps** (which produce about three units of energy in the form of useful heat for each unit of electricity input, using available waste heat as input). Innovation, and the resulting increased production volumes, will decrease heat pump costs and make them more attractive. Another innovation objective is to increase the temperature that these heat pumps can deliver to 250°C in 2030 and 350°C in 2035, increasing the range of processes in which heat pumps can be used significantly. Because heat pumps deliver a multitude of the electricity consumed in the form of heat, their application also increases the energy efficiency of processes significantly—and the available renewable electricity is used as well.

**Electricity-based heating technologies**
*Section 6.4.2*

Where higher temperatures (e.g., 800°C or more) are required, these are typically delivered by **furnaces and kilns**, fuelled by natural gas, coal, waste, and/or biomass. While the feasibility of electrical kilns for the cement and the lime industry is not fully known, for the chemical industry (ethylene plants, also called naphtha crackers), the ceramics industry, and for refineries, electrical furnaces or kilns eliminate most or all GHG emissions. In some applications, the heating will be done differently, in other applications switching to electrical furnaces or kilns offers the potential to also deliver efficiency gains in the process (for example for ceramics drying/sintering). Several technologies can also be applied below 800°C. Many different electric furnace or kiln technologies are being established, but still require some development. The aim is to have these fully developed for applications in 2040. The price of renewable electricity needs to be sufficiently low to make these investments attractive.

## 4.6 Electrification to directly drive processes

**Electrochemical conversion**
*Section 6.5.1*

Only a few processes (like aluminium and chlorine production) are currently driven by electricity, but most rely on heat to provide the energy input to drive the reactions. With an increasing share of renewable electricity, driving more reactions electrically using electrochemical conversion becomes attractive. This can be done in the chemical and the steel industry, to make fuels and potentially to produce cement by electricity. In some cases, these reactions use $CO_2$ as one of the raw materials, but conversion could potentially be more direct (and more energy efficient) than with the processes described in the Carbon Capture and Utilisation chapters. Steel, potentially cement, and ammonia can be **electrochemically** produced. Often, electrochemical reactions have no GHG emissions at all, and they do not produce waste that would need landfilling. There are many similarities between the innovation needs for the electrochemical processes in the various sectors, and technologies are expected to mature gradually, to enable applying them to process emitting a relevant share of the GHGs before 2050.

**Electrically driven separation**
*Section 6.5.2*

**Separation** of different components requires high amounts of energy. A wide range of electrically or pressure-driven technologies are being developed for a wide range of applications. For water-based separations, these technologies enable cleaning waste water sufficiently to allow its reuse in the process industry and to reduce the cost of separation of bio-based materials from the water in which they are formed. In the chemical industry (and refineries) these technologies offer the potential to replace the high thermal energy demand of distillation by much lower electricity consumption, at the same time eliminating GHG emissions. These technologies can also be used to recover valuable components from mixed gaseous waste streams, which is increasingly relevant when combustion processes are avoided.

## 4.7 Integration of hydrogen production, use, and storage

**Introducing hydrogen in industrial processes**
*Section 6.6.2*

As an energy carrier, hydrogen has a key role in the energy transition. It is already used heavily in the chemical industry and in refineries and will increasingly be used as feedstock (for CCU) in these sectors. But hydrogen can also be used as reducing agent when producing steel and non-ferrous metals or combusted in furnaces/kilns to generate high temperature heat for various sectors. **Integrating hydrogen** in these production processes often requires serious changes to the furnaces/kilns, as hydrogen burns differently than the currently used fossil fuels. For these applications where innovations deliver successful in integration of hydrogen, the combustion related GHG emissions are reduced to zero.

One of the key future production routes for hydrogen is electrolysis of water, where water decomposes into green hydrogen with oxygen as a by-product. The formed **oxygen can replace air in combustion processes**, saving significant amounts of fuel in furnaces. Using oxygen symbiotically in combustion processes enables more efficient capture of the resulting $CO_2$.

**Alternative hydrogen production routes**
*Section 6.6.1*

Replacing fossil fuels by hydrogen reduces emissions when the hydrogen is produced without (much) GHG emissions. The Fuel Cells Hydrogen Joint Undertaking is leading the development of production of green hydrogen and of blue hydrogen (traditional natural gas-based production of hydrogen, combined with CCS). Within SPIRE-CCNI, various **alternative hydrogen production** routes will be developed, all having their own advantages:

- *Pyrolysis of natural gas* requires only a low amount of energy, and produces solid carbon as valuable by-product
- *Electrolysis of $H_2S$* uses a similar process as the production of green hydrogen and produces sulphur as valuable by-product
- *Photoelectrocatalysis* directly converts solar radiation into the energy required for the decomposition of water, but as no electricity needs to be produced as intermediate step this process is more energy efficient than the production of green hydrogen
- *Thermo(electro)chemical water splitting* produces hydrogen using a metal oxide which is continuously regenerated
- *Gasification of biomass* can produce hydrogen and carbon monoxide from low value biomass remaining in a bio-based Hub4Circularity/biorefinery, after all valuable components have been harvested

Many of these production routes are not yet competitive. They need to be developed further, and where renewable electricity is used, there is a need for electricity costs to come down further.

**Hydrogen storage**
*Section 6.6.3*

Many of the new hydrogen production processes are based on renewable electricity/solar radiation, and thus on energy sources that are intermittently available. This creates a need to **store hydrogen**. Various storage options exist for hydrogen storage, including hydrogen carriers, such as ammonia. These storage applications require further development before they will be ready to enable the increased use of hydrogen.

## 4.8 Capture and purification of $CO_2$

Capture and purification of $CO_2$ from flue gases is possible. However, its relatively high cost limits the potential for commercial application in many cases. The available technologies have mainly been developed for the purpose of CCS, for which the $CO_2$ output needs to be relatively pure. While this is a prerequisite for CCS, for CCU applications the requirements vary widely. Often, other technologies can be used that match better with the specific requirements of the CCU application. A better match often translates into lower capture costs. Additional challenges are related to the sustainability of the materials used in the technologies (e.g., membranes or absorbents) and the durability and recyclability of these substances.

**Capture and purification of $CO_2$**
*Section 6.7.1*

**Flexible CO2 capture and purification technologies** should on the one hand focus on more efficient and modular post-combustion capture technologies (where the starting $CO_2$ concentration is relatively low), and on the other hand on purification technologies for $CO_2$ streams that already are at a higher concentration. Since cost reductions are key, this programme aims to target both CAPEX (-20% in 2030) and OPEX (substantial energy savings in 2030). The programme serves as an enabler for CCU, where it can contribute to substantial $CO_2$ emission reductions. Currently several kilograms of waste are generated with each $tCO_2$ captured, and the programme aims to reduce this waste drastically. Key success factors for this innovation programme are effective polices, a demand for $CO_2$ in CCU applications, and technologies that increase the $CO_2$ concentration in industrial flue gases.

Towards 2050, the programme aims for a 50% CAPEX reduction and additional energy savings. Direct air capture technologies (that work for even lower $CO_2$ concentrations) might be needed in the future as an alternative to capturing $CO_2$ from flue gas. The development of direct air capture can build on the other capture technologies.

## 4.9 $CO_2$ to mineralisation

Several types of minerals naturally bind to $CO_2$ (for example, olivine or caustic lime). This property of the material can be used to bind captured $CO_2$ and avoid this $CO_2$ being emitted and contributing to the GHG effect. There are several key applications where this form of CCU can have a big impact after the full development of the technology:

**$CO_2$ to minerals**
*Section 6.8*

- **Curing of pre-cast concrete:** Technologies exist for special concrete types (wollastonite) to bind $CO_2$ during curing to create a stronger concrete. Similar curing technology needs to be developed for regular cement types to scale up the application. When being applied to the 20% of the concrete market where it is possible (i.e., pre-cast concrete) it can reduce GHG emissions by around 13 $MtCO_2$.
- **Recycling of construction materials:** After its lifetime, concrete is ground to small pieces that are reused, and in this grinding process also fines are created. When treating these fines with $CO_2$, a material is created that can be used in new cements. With innovative technologies, up to 20% recycled fines can be used in cement in 2030 and up to 40% in 2050. GHG savings of around 5 Mt $CO_2$ are unlocked by this technology as well as a significant reduction in concrete waste.
- **Re-carbonation of natural minerals for construction materials:** Similar to the concrete fines, there are also naturally occurring minerals that bind to $CO_2$ (e.g., olivine or serpentine). These minerals can be carbonated with emerging technologies to produce

materials that can substitute current building materials. As coal phases out, the fly ashes that are created and that are currently used as building material can potentially be substituted by carbonated natural minerals. The technical potential GHG reductions can be up to 10 $MtCO_2$, but the business case is to be further explored.

$CO_2$ of pre-cast concrete and recycling of fines with $CO_2$ are in-factory processes, needing a $CO_2$-atmosphere. This can be connected to making modular concrete construction materials and can be part of recyclable housing (modular buildings) and as an integrated part in hybrid construction materials (wood, concrete, steel).

Policies on waste and GHG as well as standards for construction materials are necessary to provide incentives for users to switch from their current materials to carbonated minerals.

## 4.10 $CO_2$ and CO valorisation to chemicals, polymers, and fuels

Captured $CO_2$ or CO can be used as a feedstock, replacing fossil feedstock in the production of chemicals (including polymers) and fuels. By doing so, a large share of direct GHG emissions from the chemical industry and refineries can be mitigated, and end-of-life emissions of chemical products (e.g., when incinerated). A wide range of technologies can be used to create many different chemical products (Figure 12), which can be further transformed with the already available and new processes to other many other chemicals and fuels.

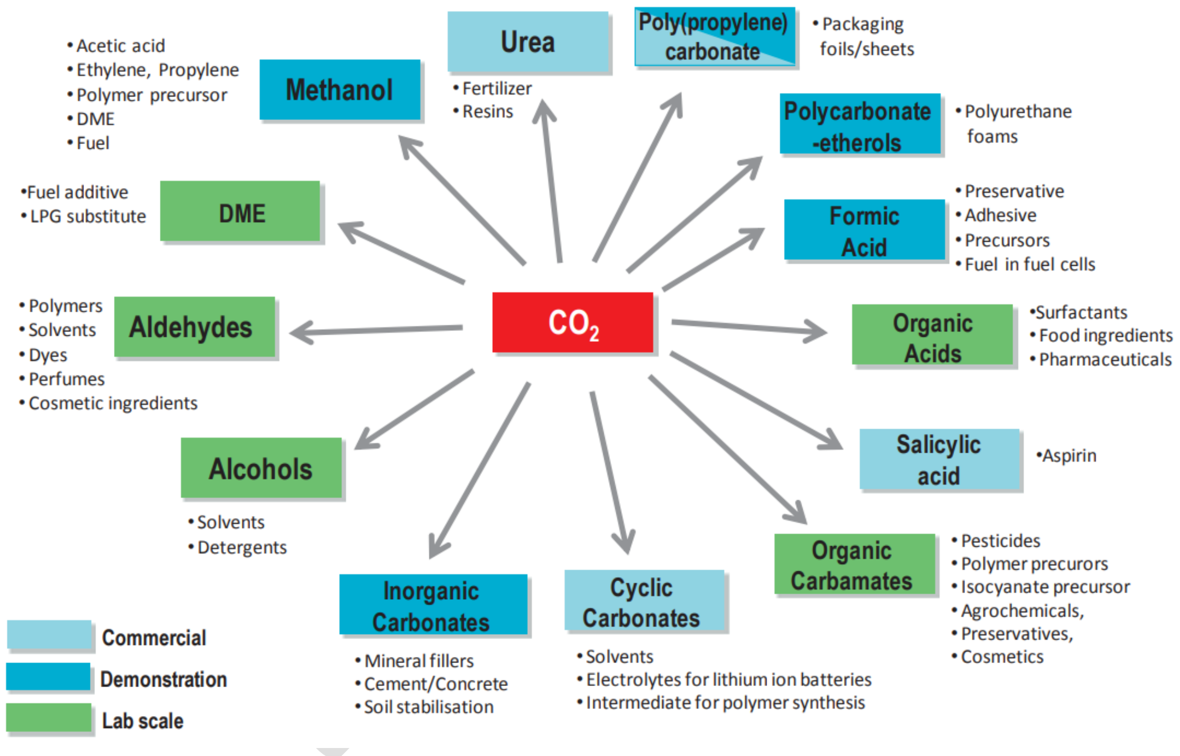


**Figure 12: $CO_2$ utilisation routes towards chemical materials, and their status of development (DECHEMA, 2017)**

Due to the many routes and target molecules, a broad portfolio of innovations is to be explored, developed, and deployed.

Most of the technologies rely on electricity or hydrogen to drive the reaction, together with a catalyst, that transforms $CO_2$ and other inputs like water to useful chemicals or fuels. Some of the technologies are already near commercial application. However, most technologies for **catalytic conversion to $CO_2$** are at a low level of maturity and require more development and demonstration in an integrated manner.

**CO₂ to chemicals, polymers, and fuels**
*Section 6.9*

Whereas most CCU processes produce chemical building blocks, it is typically more efficient to **directly use $CO_2$ in the formation of polymers** (i.e., long strands of molecules). This technology is only possible for certain polymers where most of the $CO_2$ molecule remains intact and is integrated into the polymer. The first pilots for such technologies are underway, and the aim is to be able to create polymers with 15%-30% of $CO_2$ integrated in 2030 and 20%-40% in 2050. The remainder of carbon feedstock can be delivered by other zero-carbon technologies. However, the increased efficiency of the process boosts competitiveness.

Besides electricity or hydrogen-driven technologies other technologies emerge that directly use sunlight to produce building blocks for chemicals or fuels. This **artificial photosynthesis** technology is still immature and not economic. A portfolio of projects for different technology options will be developed until 2030 and the best technologies will be deployed post-2040.

Besides $CO_2$, CO can also be used to displace fossil feedstock. CO is produced in the steel sector and in smaller volumes elsewhere. Most of the CO from steel production is used to generate electricity, but **CO can also be transformed into chemicals and fuels**. Different technologies are being tested and need to be demonstrated in an integrated manner.

If emissions of concentrated fossil CO/$CO_2$ take place, capturing these and using them often reduces overall GHG emissions and contributes to the transition. In a climate neutral 2050, however, there will no longer be emissions of concentrated fossil CO/$CO_2$ emissions, and non-permanent CCU applications should be fed with either $CO_2$ from biomass, or with $CO_2$ from direct air capture.

**Text box 1 – CCU's contribution to circularity**

$CO_2$ and CO-based products do not only contribute to the reduction of $CO_2$ emissions, but also give currently emitted $CO_2$ a value and thus play a key role in the transition to circularity.

Whereas currently carbon feedstock is abundant (in the form of fossil feedstock or $CO_2$ emissions), carbon will need to come from other sources when greenhouse gas emissions have been reduced to zero. CCU technologies are a way to close the carbon loop.

For all CCU technologies, standardised frameworks are required to compare technologies and select the most promising ones for further development. Additionally, large quantities of affordable electricity and hydrogen are required.

## 4.11 Novel process for optimised use of virgin and secondary resources

Only 12% of the material resources used in the European process industry currently are recycled and recovered materials. To move towards a truly circular and sustainable process industry using its resources consciously and without landfilling, breakthrough innovations aiming at **maximising use of secondary materials** are pursued for:

**Innovative processes to maximise use of secondary materials**
*Section 6.10.3*

- The separation and sorting of secondary materials, which combined with digitalisation enable robust processing of secondary resources with larger variations in composition/quality.
- New technologies that enable recycling, either in the same sector or in other sectors. A wide variety of recycling options will be developed at increasing scale quickly, and more and more recycling options are under development for other sectors.

Waste policies, and the manner society collects waste, are key enablers of successful prevention of landfilling and maximised use of secondary resources. Hubs for Circularity are important enablers in the optimisation of regional waste flows. Success will also depend on the tenacious



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(public) mapping of waste streams and developing and sharing knowledge about technologies and applications to reuse these in the best manner for the specific location.

**Breakthrough resource efficiency**
*Section 6.10.4*

Existing and new processes will benefit greatly from radically new processes with much higher energy efficiency and selectivity, producing less by-product/waste. These benefits will (among others) be delivered by **process intensification**, disruptively changing and combining the manner functionalities are delivered. Equipment will be made much smaller, enabling much better control of reactions. 3D printing technology allows the production of new equipment, unlocking new possibilities. Processes will also be optimised towards near zero production of non-recyclable waste by optimising product specifications, process control, and increasing the re-circulation of off-spec materials in the process. This will lead to significant energy and resource savings, mainly in the chemical industry, the full effect being delivered after 2030.

Due to their economies of scale, large-scale plants typically have higher efficiencies than small-scale plants, but the transition to a circular economy requires part of the processes to be done close to the source of materials that have a relatively low energy density, like waste or biomass. **Modular** solutions will be commercially available in 2030, which allows for small-scale conversion at the best locations with the efficiency of large-scale plants.

**Advanced catalysis**
*Section 6.10.1*

To get these new processes going, and to enable many of the new technologies and reactions described in several other innovation areas, **delivery of new catalysts** is essential. Catalysts accelerate reactions without being consumed, and a low amount of exactly the right catalyst can significantly increase yields, reduce waste production, and reduce energy consumption. Catalysts have been developed for many decades, but their development is speeding up considerably by coupling machine learning and artificial intelligence with high throughput catalyst testing technologies. New types of catalysts unlocking new possibilities will grow continuously from the existing catalyst families (heterogeneous/homogeneous catalysts), and new families of catalysts (directly) using renewable energy (photocatalysis and electrocatalysis) will establish themselves around 2040.

**Re-use of water and materials contained**
*Section 6.10.2*

These catalysts, new (electrically driven) separation technologies and many other innovations will also enable **a new approach towards industrial waste water**. The approach will transition from "making it ready for discharge" towards "making ready for full reuse," including the recovery of solids, solubles, and fully reusing the water in the process industry, with (hardly) any discharge of water and without a need for landfilling. In parallel, processes will be developed producing less wastewater, especially relevant for bio-based processes currently producing high volumes of waste water.

## 4.12 Minimising the environmental footprint of materials

New materials (and their products) developed will simultaneously optimise technical and ecological performance over their full life time. This means:

**Innovative materials from the process industry**
*Section 6.11.1*

- A real opportunity exists to develop new materials with optimized technical performance that would in turn improve their ecological performance. This means developing **innovative materials from the process industry** (reacting to stimuli, lighter and with in situ (de)functionalisation) would offer totally new opportunities. Perhaps the amount of materials needed would be lower, but the materials that would still be produced would be used more intensely, unlocking a step-change in added value and facilitating the transition of the other sectors. The European process industry is continuously improving the materials they produce; this innovation programme adds focus on cross-sectoral development of new materials specifically aimed at reducing GHG emissions in their lifecycle and landfilling.

- The process industry has optimised its materials towards maximum functionality through ingeniously combining materials (multilayer plastics, composites, etc.). These materials often cannot be recycled conventionally but can be co-processed where they provide both a source of energy and a secondary material. This is the preferred option over incineration or landfill and will deliver the best performance over the full value chain. Developing materials with better **inherent material recyclability** will mainly happen after 2030.

**Inherent recyclability of materials**
*Section 6.11.2*

## 4.13 Process technologies for industrial-urban symbiosis

*"Industrial(-Urban) Symbiosis is a system approach to a more sustainable and integrated industrial(-urban) system, which identifies business opportunities that leverage underutilised resources (such as materials, energy, water, capacity, expertise, assets, etc)"* – based on the definition by (Lombardi & Laybourn, 2012). *"It involves organisations operating in different sectors of activity that engage in mutually beneficial transactions to reuse waste and by-products, finding innovative ways to source inputs and optimise the value of the residues of their processes, e.g. by using waste or by-product from one activity as an input for another activity."*

To make such interactions possible, Industrial-Urban Symbiosis is making use of technologies already described in detail in other innovation programmes (as can also be observed in Figure 10). These can be for example decontamination and separation technologies to purify flows or obtain desired components from mixed flows, recycling technologies, technologies allowing for flexibility in raw materials and energy, or digital technologies for optimisation of flows across companies. Whereas these and further relevant technologies are elaborated in other innovation programmes, here we are dealing with their demonstration and implementation for cases across company limits.

Demonstrating the feasibility of the concept of **Industrial Urban Symbiosis** (IUS) using the right selection of the technologies to address individual industrial use cases is the aim of this innovation area. The cases to be demonstrated will vary depending on the regions and the co-location of industries there and the presence of specific material flows. Therefore, even if generic approaches and technologies will be implemented, the cases will be specific. Demand for certain material flows (recycled waste or by product) may also differ per region, depending on which application is most desirable from an economic and environmental perspective. The IUS demonstration projects will focus on water, energy, $CO_2$-containing gases, and/or materials (both urban and industrial flows). The demonstration will take place before 2030 to showcase the possibilities and prepare for wide-scale deployment.

**Industrial-Urban Symbiosis**
*Section 6.12.1*

## 4.14 Business models and demonstration of I-US

SPIRE-CCNI aims to support the creation of **15 mature H4C by 2030 and 50 H4C by 2050**. Such hubs will facilitate the development of region-specific business cases, using available business models or developing new ones, and engage with stakeholders to set up collaboration projects leading to the demonstration and deployment of Industrial-Urban Symbiosis and circularity. In order to avoid fragmentation, however, there will also be a need of establishment of a common platform for regional H4C for knowledge creation, best practice exchange and training to connect the Hubs on the EU level and use the synergies to accelerate the progress. The 15 H4C in 2030 will act as lighthouses that lead the further development of the H4C concept and widespread adoption of this model across Europe.

To achieve this, two innovation programmes are developed: one that supports the set-up of regional H4C, and one Community of Practice to serve as a common platform (see Figure 13):

- **Hubs for Circularity:** As confirmed by Klaus Sommer in his report on Industrial Symbiosis, well-organised facilitation is the basis to promote Industrial-Urban Symbiosis and circularity

**Hubs for Circularity**
*Section 6.13.1.*

and drive their implementation. Hubs for Circularity are expected to take this facilitating and leading role, supported by SPIRE-CCNI. They will be neutral towards the regional industries, enabling them to address conflicts of interests appropriately. They will be regional stakeholders, which will build trust and foster collaboration. The Hubs will analyse and scout the region, collecting knowledge about the specific flows present there that can become feedstocks, potential implementation and needs for technologies to process them. They will develop business cases and ignite discussions with potential partners for symbiosis, display benefits for all involved and connect to possible sources for funding that can help to implement symbiosis as well as circumventing barriers. In this sense, they will develop an innovation business plan for the territory. SPIRE-CCNI can provide support for research, development, and innovation (RDI) activities through the other innovation programmes to provide solutions to the H4C territory. Through the H4C SPIRE-CCNI can gather information to align its innovation programmes and calls with the identified needs. The objective is to achieve self-propelling structures that find a sustainable business-to-territory and co-financing model to continue the transition without funding at some point.

**Cummunity of practice**
*Section 6.13.2*

- **Community of Practice:** H4Cs and SPIRE-CCNI-supported facilitators should be interconnected to create synergies and to make skills and knowledge sustainable. Such interconnection should facilitate access to sources of knowledge, fertilise ideation, talent and innovation within each H4C—across Hubs and with other initiatives. This EU-wide network of networks is called the Community of Practice. Figure 13 illustrates how the Community of Practice coordinates and exchanges knowledge, tools and best practices, to accelerate deployment of solutions towards climate neutrality, circular economy and competitiveness. This can be technical (e.g., guidance on I-US) or non-technical (guidance on how to create the right culture). Collaboration and connection with other initiatives such as the EIT clusters (e.g., Climate KIC or EIT Raw Materials), the Digital Innovation Hubs or other pan-European initiatives can also play an important role.

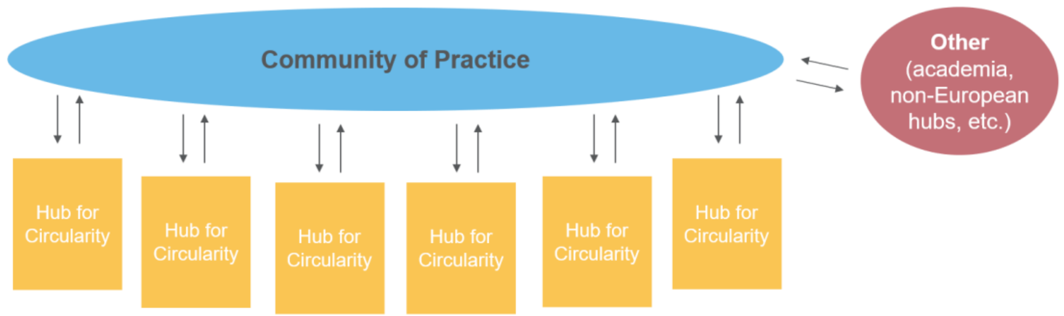


**Figure 13: Community of practice – connecting hubs for circularity across the EU**

## 4.15 Introduction to digitalisation

Digitalisation is recognised as the source and driver for the transformation of process industries to zero GHG emissions and zero waste reduction, it will enable the fast development of new materials and processes and of industrial-urban symbiosis and making a major contribution to improving the energy and resource efficiency of the existing plants and supply chains. To strengthen its global competitiveness in a turbulent economic environment and the transition into a carbon-neutral and zero-waste economy, the SPIRE-CCNI process industries must reap the full benefits of what digital technologies have to offer today. The change will happen horizontally and cover the entire life cycle, including R&D, plant operations, supply chain management, customer relations and integrating material flows in a circular economy, and across industry sectors. Digital technologies will be powerful and disruptive cross-cutting enablers for the transformation of the European process industries. Digitalisation will have social, ecological, and economic impacts. It will make processing plants and operations more agile and resource and energy efficient, contribute to significant reductions of $CO_2$ and other emissions reductions, orchestrate the pathway to a carbon-neutral economy, improve safety and working conditions, and contribute to securing competitiveness and jobs in the European process industries over the next decades.

Digital technologies act as key enablers for various other innovation areas and programmes, such as industrial and urban symbiosis, integration of renewable energy carriers, enhancing flexibility and diversity of energy and resource inputs, innovative materials, and new business models.

Examples of innovations by digitalisation are:

- Faster and more cost-efficient development of sustainable materials and processes;
- **Digital Twins** that enable simulation and optimisation of plants and materials over the whole life cycle and are continuously updated as the plants and processes evolve, and new data becomes available
- **Novel reliable and sensing capabilities at reduced cost** for process monitoring and tight control, multi-sensor data fusion and data analytics for the detection of abnormal states, and the accurate prediction of the remaining lifetime of equipment
- **Lights-off plants** by advanced control and equipment monitoring using **data analytics and machine learning**
- Integrated **resources and production management of plants and industrial parks** for optimised sustainability and industrial symbiosis
- **Optimisation of the use of electric power from renewable sources** (demand-site response) by adaptive operation
- Digitalisation of **value chains** from the sourcing of raw and secondary materials to the end user, digital fingerprints of materials to facilitate down-stream processing and recycling, optimisation of logistics
- New forms of **collaboration of operators** and plant managers with advanced control and optimisation systems, through rich but easy to comprehend visualisations

The success of digital solutions will depend on several factors:

- **Training of the existing and future workforce is required** to make optimal use of the emerging capabilities of digital technologies.
- **Cybersecurity must be ensured**. The deployment of digital technologies will increase the vulnerability to cyberattacks, which pose significant risks for plant safety and efficient plant operations. The process industry is an important stakeholder and should play an active role in developing solutions to increase cybersecurity.
- **Organisation must get ready**. A digital strategy is needed to integrate digital systems and platforms in the organisational structure, set the responsibilities clear and secure time of staff.
- **Co-create with digital firms and industry partners** to design the best solutions in limited time.

The Innovation Areas covering digitalisation are structured as following:

**1. Digitalisation of the design phase of processes and materials**. Through data and information sharing within and across value chains, with customers and within the R&D-ecosystem topics like recyclability of end-of-life products can be integrated in the early design phase of materials and the processes to make these materials. Furthermore, advanced modelling and applying digital twins and other digital solutions to design materials and processes can speed up the design phase, shorten time-to-market and result in processes with higher energy and resource efficiency, and contribute to flexibility and enhanced safety of operations.

**2. Digitalisation of plants**. Digital technologies such as advanced sensors, model predictive control, and real-time optimisation are needed to operate in a flexible and agile manner but nonetheless higher efficiency and reliability. Reliable predictions of remaining lifetime and predictive maintenance will significantly reduce unplanned shutdowns and lead to improved efficiency.

**3. Digitalisation of connected processes and supply chains**. Digital technologies can help to improve the management of highly connected processes to ensure efficient use of production assets, resources, and energy while safeguarding quality, yield, and reliability. Supply chain digitalisation will happen within a company or production chain, integrated with the upstream and downstream value chains, and across industries and within regions and municipalities (urban-industrial symbiosis).

The programming of the innovation programmes is up to 2030. Given the speed of innovation of digital technologies, the programme focuses on a 2030 timeline, the horizon beyond can be added in the regular updating of this roadmap, following new insights on the fast-evolving digital technologies that will be available by that time.

## 4.16 Digitalisation of process/product R&D

**Digitalisation of process/product R&I**
*Section 6.15*

Digital technologies will increasingly be applied in the different stages of product and process development. They will enable to integrate life cycle thinking and advanced sustainability assessments throughout the development process. Innovation will be accelerated, leading to more efficient and much faster idea-to-market processes. One challenge is to embed customers into the R&D-process. With the increasing complexity of connected industries in a circular economy, this becomes even more important.

Digital technologies will improve all development phases of innovative materials. On the one hand, this consists of new forms of data sharing with customers and other stakeholders in the supply chain. On the other hand, new models and simulation tools will need to be developed to characterise the performance of new materials already in the design phase. The design of production plants will be significantly improved with respect to reliability, speed, and cost by moving further in the direction of model-based design processes. Ultimately, the design of materials and plants and the operation of the plants will be supported by digital twins that embody all available information in a condensed form that can be used for predictive simulations, troubleshooting, optimisation, and continuous improvement.

Digital solutions that are needed are:

1. Improve material design process:
   - Further development and integration of modelling and simulation tools, connecting the use and end-of-life phases to the materials design phase
   - More efficient materials design processes by combining data and models in different forms and from different sources
   - Development of digital tools for effective and intelligent data and knowledge management

2. Integration of materials and formulation design with process design:
   - Include information about the production process and the feedstock into the materials design phase
   - Develop detailed characterisation methods of (secondary) feedstocks as input for more flexible processes

Digital technologies can also support the design of processes using digital twins. Process design is increasingly done using faithful predictive simulation models of processes, pieces of equipment, and plants. However, several aspects still prevent the use of the full potential of the model-based approach:

- Fundamental data, e.g., of thermodynamic properties or kinetics is missing and expensive to generate experimentally
- Building fundamental models is a demanding process that absorbs the capacity of high-level experts over long periods of time, so that many process elements are not described by rigorous models
- Dynamic models that can describe the reaction to changeovers of materials and feedstock or load changes, e.g., in response to the availability of green electric power are usually not available
- Models for the design phase are rarely used in the production phase of the life cycle of the process, and information on the behaviour of the real plant and on its modifications is rarely fed back to the design model

The objective is to disruptively transform how process engineering is done today, by moving to fully model-based process design within the process industry including the objective to develop a digital twin ecosystem.

The digital design of processes contributes to the SPIRE-CCNI objectives. It will speed up innovation through efficient simulation of process parameters and allow to incorporate energy and resource efficiency already in the design phase. Consequently, digital design of processes can also enhance the competitive edge of the European process industry.

## 4.17 Digitalisation of plants

**Digitalisation of plants**
*Section 6.16*

Industrial processes and related process chains are increasingly complex. This is triggered by several trends, like the market demand of new and more customised products with new features and higher demands on the production plants, the need of more flexibility towards alternative feedstocks (e.g., waste, biomass, $H_2$, $CO_2$), process electrification to make use of renewable energy sources.

New digital-enabled solutions are necessary to improve process control and operations as well as plant reliability. Significant gains in efficiency (e.g., reductions of downtime, reduced usage of raw materials and energy) can be achieved because of less rework and less waste in each production facility.

The movement towards a circular economy and the utilisation of electric power from renewables will put much higher demand on the flexibility of the plants and processes, in terms of load variations, variations of feedstock, and variations of product specifications.

The switch to more sustainable and flexible production increases the need to develop integrated physical and soft-sensor measurements combined with advanced modelling of all critical product quality attributes. Automated feedback and closed-loop control of the relevant parameters of the materials and of the processes ensures efficient operation, reduced material variability, thereby preventing materials being rejected further down the supply chain, and flexibility with respect to types and amounts of materials as well as varying availability of feedstock and utilities.

On a higher level, model-based plant and sitewide visualisation and optimisation of energy and resource efficiency and other relevant indicators as the $CO_2$-footprint will lead to significant reductions of the ecological footprint of the process industries.

The digital solutions consist of digital models of processes, decision support systems, and predictive control techniques. Novel powerful and intelligent sensors and sensor networks that provide reliable information especially about the properties of materials or streams of material at reduced cost are necessary, and solutions to handle the huge amounts of online data coming from these sensors must be available.

The aim is to develop highly flexible, easy to handle, and generally applicable solutions for the optimisation of processes and complete process chain of a company, and even between different companies and industries. Digital twins for plants, processes and materials which can communicate with each other in a highly flexible way and be employed to solve complex sitewide optimisation problems are an important element of these solution. In 2050, a company will have access to large amounts of accurate, curated, and readily accessible operational data to support process monitoring and process optimisation.

Digital tools are needed for plant control and optimisation so that the plants can be operated in a fully energy and resource and environmentally friendly way. These tools provide the basis for the realisation of lights-off plants that are monitored remotely by a small crew and where maintenance and improvement measures are performed in a planned and coordinating fashion with the least possible disruption and resources. Developing these digital solutions will result in:

- Demonstration of fully dynamic and model-based control of single processes
- Coordination and optimisation of the control of interconnected processes in a process chain
- Decision support systems for all processes and process chains where model-based online control is not yet possible
- Early detection of possible cyber-attacks to process control systems and triggering of suitable counteractions as soon as possible
- Development of an ecosystem of suitable digital twins of plants, processes, and materials

Intelligent sensors and sensor networks, data processing, and predictive maintenance tools need to be developed. For the operation and management of complex plants in the process industries, the availability of online information about the plant, the process, the environment of the process, and product quality attributes are essential. Without such information, process control, production scheduling, material allocation, energy and pollution reduction, and efficient maintenance actions are not possible. Powerful and intelligent online sensors or sensor networks are necessary, and solutions have to be available to handle the huge amounts of online data coming from these sensors and to extract useful knowledge out of them.

These digital tools will eventually result in:

- Powerful and intelligent online process sensors or sensor-networks with focus on the properties of resources and materials, environmental aspects of the plants and processes as, e.g., energy usage and emissions, and on predictive maintenance
- Solutions for automatic pre-processing of the large amounts of data coming from plants, processes and materials
- Automatic real-time extraction of knowledge from large amounts of process data
- Solutions to detect possible equipment failures early automatically by intelligent condition monitoring system
- Expanding process monitoring systems by methods to reveal the full environmental footprint of the running process in real time
- Integration of LCA aspects into the plant and sitewide monitoring strategies

## 4.18 Digitalisation of connected processes and supply chains

**Digitalisation of connected processes and supply chains**
*Section 6.17*

Supply chain digitalisation can occur on different levels:

1. Supply chains within a company or single production processes: planning and scheduling can be improved to optimise efficiency and reliability of supply in the presence of uncertainties on raw materials, prices, or resources.
2. Integration of the upstream supply chain: procurement and predicted deliveries are integrated into the planning to optimise not only on company level but on the full upstream supply chain level to achieve efficiency improvements that reduce the carbon footprint.

3. Full supply chain: integrated optimisation of logistics, energy, and industrial symbiosis but now also with downstream actors. Additionally, it includes integrated waste management (waste water treatment, thermal treatment, other by-products, etc.) optimisation.

The first two levels can be supported by a set of digital solutions for integrated planning, scheduling, and control within plants and upstream supply chains. Developing digital solutions that can assist managing complex processing and supply chains dynamically is a key challenge. This allows for energy and resource efficiency, a quick response to changing customer demands for prices for raw materials and energy, and the availability of green power to be realised simultaneously. More specific targets that are addressed are:

- Develop solutions for integrated planning, scheduling and control within plants to optimise efficiency and reliability of supply and addressing the trade-off between the maximisation of throughput and resource and energy efficiency.
- Integration of production planning and scheduling with the provision of utilities (e.g., steam, electric power, waste treatment) and electric-power procurement, adaptation to the supply of electric-power from renewables, demand side management. Integrated management of production with waste and wastewater treatment.
- Integration of planning and scheduling along the supply chain, including real-time integrated logistics, procurement, and production optimisation and real-time cradle-to-gate resource efficiency and LCA monitoring and optimisation.
- Data integration and along the supply chain and across sectors, considering protection of IP and commercial interests and development of platforms that implement these concepts.
- Facilitation of reuse and recycling by digital fingerprints of products and materials along the supply chain, based on standardised product descriptions (see also IP 5).
- Real-time characterisation of waste streams (see also IP5), enabling an increase of the use of secondary materials.

The third level, full supply chains, needs the development of digital technologies that enable industrial-industrial and urban-industrial symbiosis.

Efficient industrial symbiosis requires a continuous adaptation of all parties involved to variations of supply and demand such that the overall energy and resource efficiency is maximised, the environmental impact is minimised, and all partners have economic advantages. The integrated operation, planning, and scheduling of large interconnected industrial plants and sites is already a major challenge (see the previous innovation programme). In industrial symbiosis, companies with individual business goals and technical and economic constraints about which they do not want to share information freely are tightly connected, so an overarching coordination and distribution of benefits is becoming necessary.

When progressing to urban-industrial symbiosis, uncontrollable and partly unforeseeable behaviours of consumers and the presence of complex connecting infrastructures (e.g., the collection and sorting of waste streams) makes an integrated management even more complex. Digitalisation is key to handling these challenges to arrive at integrated, energy and resource efficient, environmentally benign, and economically competitive systems.

At the level of the full supply chain, digital solutions can achieve:

- Integrated real-time systems management solutions for industrial symbiosis that support industrial and urban-industrial water and waste-water treatment and distribution systems and the utilisation of waste heat by industry and municipalities. These management systems should also target model-based optimisation solutions for connected production units under different ownership.
- Digitalisation of the classification and sorting of waste streams, providing real-time feedback on the composition of the streams that are exchanged, advanced sensing for the sorting of waste, and ultimately digitalisation of the full value chain from the ingoing

waste streams to their processing and the delivery of feedstock to the process industries so that the composition of the streams of the processing units is predictable and the whole chain can be operated in the most efficient manner.

- Digital tracing of materials and the real-time brokerage of waste streams, including real-time access to information on material compositions during the complete life cycle, standardised formats for the digital characterisation of materials and information systems that provide full and transparent information on all major waste streams and facilitate the exchange of these streams for material re-processing or reuse.

# 5 Synthesis

*<<the focus has been on the individual pieces of the roadmap and this chapter will be expanded and polished up after the stakeholder consultation>>*

## 5.1 Aggregated SPIRE-CCNI roadmap

<< the aggregated findings of the roadmap will be added after the stakeholder consultation. So far only, the part on hubs for circularity are included>>

The overview of the innovation programmes (Figure 10 and Figure 11) in Section 4.1 shows already the many cross-sectoral innovations that are required across factory and sector boundaries to meet SPIRE-CCNI's ambitions of becoming climate neutral and circular while remaining competitive. The **Hubs for Circularity** serve as a key accelerator to bring stakeholders together, find common problems, and solve them in collaboratively. Through the H4Cs, and supported by the Community of Practice, the key technologies can be demonstrated before 2030 and rolled out effectively across Europe.

## 5.2 Human capital

*<<will be added after the stakeholder consultation>>*

## 5.3 Competitiveness

The innovations delivered by SPIRE-CCNI will improve the competitiveness of the process industry compared to a scenario in which the ambitions (zero GHG emissions, near-zero landfilling, and near-zero waste water discharge) would need to be delivered without these innovations) because:

- New energy efficiency measures become available, reducing energy costs.
- New applications for the use of secondary materials become available, increasing the options to recycle materials (without which the near-zero landfilling ambition would become difficult/impossible to reach).
- The increased technology options developed under SPIRE-CCNI allow the selection of the best-fitting and least-cost option for each specific application and situation.
- Several mechanisms within a H4C boost economic growth in the region. The I-US results in efficiencies for process industries (as well as water utilities and other companies in the H4C), which saves costs (especially relevant since most of the effective options to deliver on the ambitions are often multi-stakeholder options). The hub will attract talent and investments due to the increased value of the region.
- Cross sectoral sharing of learnings accelerates the innovation speed and reduce innovation costs.

*<<will be expanded after the stakeholder consultation>>*

## 5.4 Milestones

Table 1 provides an overview of the progress of each innovation programme. For some non-technical innovation programmes this is not relevant, and for some innovation programmes the programming is not yet specified. The table shows that most of the innovation programmes will already deliver technologies that are ready for deployment by 2030.Only four innovation programmes are not expected to deliver commercial technologies at that time. The reason for this is that these areas are less mature and require more development.

**Table 1: Progress of innovation programmes over time (% of TRL9 demonstrations within the innovation programme)**

| Innovation area | Innovation programme | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Integrating renewable energy carriers | Integration of renewables | 100% | 100% | 100% |
| | Integration of bio-energy waste and other new fuels | 0% | 100% | 100% |
| | Competitive hybrid transition to low-carbon industrial energy supply | 0% | 100% | 100% |
| Enhancing energy flexibility and diversity | Flexibility and demand response | 60% | 100% | 100% |
| Enhanced utilisation of different grades of heat | Heat exchange optimisation | *<<to be added>>* | | |
| Electrification of heating processes | Electricity to upgrade waste heat | 78% | 100% | 100% |
| | Other electricity-based heating processes | 0% | 100% | 100% |
| Electrification to directly drive processes | Electrochemical conversion | 0% | 50% | 100% |
| | Electrically-driven separation | 0% | 50% | 100% |
| Integration of hydrogen production, use and storage | Alternative routes for the production of hydrogen | 36% | 73% | 100% |
| | Introducing no emission hydrogen in the industrial processes | 62% | 100% | 100% |
| | Storage of hydrogen | 100% | 100% | 100% |
| Capture and purification of $CO_2$ | Flexible $CO_2$ capture and purification technologies | 0% | 83% | 100% |
| $CO_2$ to minerals | $CO_2$ valorisation during concrete production | 50% | 100% | 100% |
| | Circular construction materials by re-carbonation | 100% | 100% | 100% |
| | Natural materials mineralisation (e.g., olivine carbonating $CO_2$) | 0% | 0% | 100% |
| $CO_2$ valorisation to chemicals, polymers, and fuels | Direct utilisation of sunlight (Artificial photosynthesis) | 0% | 50% | 100% |
| | Catalytic conversion of $CO_2$ (excluding photocatalytic and direct use in polymers) | 0% | 67% | 100% |
| | $CO_2$ (and $CO_2$/CO) to polymers | 25% | 63% | 100% |
| | CO captured from industrial waste gases to chemicals and fuels | *<<to be added>>* | | |
| Disruptive processes for optimised use of virgin and secondary resources | Advanced catalysis providing raw material flexibility and lower energy inputs through alternative chemical pathways | 20% | 40% | 100% |
| | Complete reuse of water and valorisation of the materials contained | *<<to be added>>* | | |
| | Innovative processes to maximise use of secondary raw materials | *<<to be added>>* | | |
| | Breakthrough process design for improved energy and resource efficiency | 13% | 13% | 100% |
| Minimising the environmental footprint of materials | Innovative materials of the process industries | 33% | 67% | 100% |
| | Inherent recyclability of materials | 0% | 0% | 100% |
| Process technologies for Industrial-Urban symbiosis | Demonstration of Industrial-Urban Symbiosis | 100% | 100% | 100% |
| Business models and demonstration of I-US | Community of Practice | Non-technological | | |
| | Development of Hubs of Circularity | Non-technological | | |
| Digitalisation of process/product R&D | Towards digitally supported design of environmentally benign high-performance materials | 100% | 100% | 100% |
| | Towards digital process development and engineering | 100% | 100% | 100% |
| Digitalisation of plants | Optimised plant operations control towards highest quality materials and fully energy, resource efficient, and environmentally friendly plants | 100% | 100% | 100% |
| | Intelligent sensors and sensor networks, data processing, and equipment monitoring to assess the state of equipment and materials | 100% | 100% | 100% |
| Digitalisation of connected processes and supply chains | Towards fully autonomous scheduled production processes and integrated supply chains | 100% | 100% | 100% |
| | Towards fully connected process industries—scheduling across plant networks/sites/industries/municipalities—industrial symbiosis | 100% | 100% | 100% |

*<< this overview is subject to change as the timelines are still expected to be changed after the stakeholder consultation>>*

In 2024, the progress for each innovation programme will be evaluated, as well as the portfolio of innovation programmes, to potentially adjust based on developments and steer towards the ambitions.

## 5.5 Investments

Table 2 summarises the estimated investments required for all innovation programmes. Investments required for the deployment of the technologies are excluded from this table. Where ranges are defined in the innovation programmes, the average of the range is used. The total investments needed are estimated to be €17 billion until 2050.

**Table 2: Total required investments for all SPIRE-CCNI innovation programmes in million euro (incomplete and still subject to change)** [11]

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Total |
|---|---|---|---|---|---|---|
| 2020-2030 | €641 | €2,129 | €2,769 | €1,229 | €69 | €6,836 |
| 2030-2040 | €168 | €1,052 | €2,296 | €2,713 | €73 | €6,301 |
| 2040-2050 | €0 | €686 | €1,190 | €2,405 | €38 | €4,318 |
| Total | €808 | €3,867 | €6,254 | €6,347 | €179 | €17,455 |
| *% public funding* | | | | | | |
| *Public funding* | | | | | | |

*<<please take the considerations in the foreword into account when interpreting these numbers>>*

The preliminary estimated investments are highest in the first decade (€7 billion), as most innovation is frontloaded to maximise GHG reduction impact. Investments needed decrease in the second decade (€6 billion) and third decade (€4 billion).

To put these numbers into context, they are compared to other studies:

- The market testing study for the innovation fund estimated a potential investment volume required for demonstration projects in energy-intensive industries (including industrial CCS and CCU) of €31-€42 billion (European Commission, 2019). This number has a broader scope since it includes also CCS and sector-specific technologies, but it is also described as a conservative estimate. Taking this into account the order of magnitude of investments seems to be in the right order of magnitude.
- Navigant (Navigant, 2018) calculates total cumulative investments and operational cost of €9-€15 billion to reduce 19.4 million tonnes $CO_2$e in the Dutch industry (scope 1) before 2030; for comparison, the total European scope 1 emissions of the SPIRE-CCNI sectors industry are 505 million tonnes $CO_2$e (26 times as much—and need to be abated all to arrive at 100% GHG emission reduction).[12]

## 5.6 Benefits of SPIRE-CCNI

SPIRE-CCNI is a vehicle that effectively stimulates innovation. The key benefits of SPIRE-CCNI compared to regular bilateral innovation support from government to innovators are the following:

- **Community:** SPIRE-CCNI brings various companies together and co-developed this roadmap with its members to serve as a shared vision for all members as well as non-members. A concrete plan helps to coordinate and accelerate innovation in European process industries.
- **Cross-sectoral collaboration:** As outlined in this roadmap, many solutions require collaboration across sector boundaries. An ecosystem of process industries and other sectors is needed to achieve transformational innovation. SPIRE-CCNI's cross-sectoral focus and vision of Hubs for Circularity will shape this ecosystem.
- **Long-term collaboration:** It is key that there is a long-term plan and innovators are continuously engaged for innovations to reach the market and impact society. The

[11] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

[12] The industrial sector and geographical coverage as well as the depth of the emission reduction as well as the timeline are different in this comparison and "deployment investments and operational costs" are compared with "innovation investments," so this comparison should be seen as an order-of-magnitude comparison only. Furthermore, SPIRE-CCNI also has the ambition of near-zero landfilling and near-zero waste water discharge and would likely also reduce emissions embedded in the fossil feedstocks.

innovation programmes described in this roadmap take this long-term perspective and aim for an effective pipeline of innovation all the way to deployment at scale.

- **Informed decisions:** SPIRE-CCNI's governance ensures that the same people that have on-the-ground experience working in innovation projects also are involved in shaping the calls. This means that any new insights are immediately considered in the pipeline management.
- **Knowledge dissemination:** SPIRE-CCNI develops tools and vehicles for sharing knowledge between its members so that all companies and sectors can learn from the innovative solutions that are being developed to spark new ideas. Of SPIRE-CCNI project coordinators, 60% are member of SPIRE-CCNI, which means that there is also a significant dissemination of knowledge to non-members.

# 6 Annex A: details of innovation areas

## 6.1 Integrating renewable energy carriers

### 6.1.1 Integration of renewables

This innovation programme focuses on integration of renewable energy at scale in the process industries. Although various elements for integration exist or are under development in the other innovation programmes, the technologies have never been tested together in an integrated way.

Having the energy production right next to or on the site enables reduction of transmission losses and in some cases the transformation from direct current to alternating current can be avoided. Potentially other synergies exist with renewable heat.

This programme covers all renewable energy sources, including concentrated solar power or heat (see text box 2), photovoltaic power, wind power, and geothermal heat. Biomass is excluded as this is covered in the innovation programme "integration of bio-energy, waste and other new fuels". These renewable energy sources can meet demand for high temperature heat, low temperature heat or electricity demand. Therefore, numerous applications in industry exist. Some examples are:

- Combining the emerging technology for steel making via direct electrolysis with PV and wind power generation in a location where there is enough wind and solar irradiation. The by-product oxygen could be used for a process in a nearby factory that requires oxygen. The process requires very finely ground iron ore, so a grinding installation is included on-site which can easily be turned up or down depending on wind and sunlight availability. Such an installation would likely be developed at large scale. Such a large-scale installation coupled with renewable energy installation requires large buffer to reduce the risk of disruption of production.
- Combining ammonia production with renewable electricity generation. The renewable electricity is used to produce hydrogen through electrolysis, then the hydrogen is combined with nitrogen captured from the air to produce ammonia. The oxygen from the electrolysis can be used to produce nitric acid. A storage system is present to ensure relatively constant operation.
- Combining cement production with concentrated solar heat and PV. In this case concentrated solar heat is used to get the raw materials up to around 900 °C and then the electric furnace powered by PV is used to reach the temperature required for calcination.
- Combining renewable power with $CO_2$ upgrading to CO for steel production. The renewable electricity generation can be directly used to convert $CO_2$ into CO that can be used to reduce the iron ore.

These types of projects combine technologies, which can also be technologies under development in other innovation programmes. For example, integration of green hydrogen (6.6.2 Introducing no emission hydrogen in the industrial processes) and oxygen (6.6.2 Introducing no emission hydrogen in the industrial processes) in existing plants, versatile storage or buffer system (6.2.1 Flexibility and demand response) and clever digital systems to enable 24/7 cost-effective operation in a flexible manner (6.17.1 Towards fully autonomous scheduled production processes and integrated supply chains).

**Text box 2 - Solar Heat for Industrial Processes (SHIP)**

One of the renewable energy technologies that can be used in process industries is solar heat. Although according to experts the greatest potential for solar heat is in industrial processes, the share of industry in solar heat demand remains low. Although the solar technologies are available commercially, key questions remain with regards to integration into industrial processes at different temperatures. Integration with lower-temperature processes (80-150 °C) is more mature (TRL 3-5) than higher temperatures. Especially temperatures exceeding 400 °C are immature.

#### 6.1.1.1 Innovation objectives

The innovation objective of this programme is to demonstrate the potential of integration of renewables in the process industry by three demonstration projects:

- Small scale (order of magnitude 10 MW) demonstrated by 2024
- Medium scale (order of magnitude 100 MW) demonstrated by 2026
- Large scale (order of magnitude 1,000 MW) demonstrated by 2028

#### 6.1.1.2 Impact

***GHG emissions***

At 7,500 load hours and if natural gas is displaced at 56 kg$CO_2$/GJ, the impact per project is:

- Small scale (order of magnitude 10 MW) – 0.02 Mt$CO_2$
- Medium scale (order of magnitude 100 MW) – 0.15 Mt$CO_2$
- Large scale (order of magnitude 1,000 MW) – 1.51 Mt$CO_2$

This means that this innovation programme (with 4/2/1 installation in S/M/L, respectively) will directly reduce about 2 Mt$CO_2$.

The technical potential if all SPIRE-CCNI sectors deploy the integration of renewables is higher. About one-third of emissions in SPIRE-CCNI sector are process emissions and therefore cannot be reduced with renewables as it only addresses energy-related emissions. The remaining 2/3 of direct emissions can be mitigated using integration of renewables. That is equivalent to around 320 Mt$CO_2$ today.

***Competitiveness***

This innovation programme aims to reduce energy costs (e.g., due to avoiding transmission losses). It is difficult to predict how much synergies can be achieved, that is why demonstration projects are important.

Other competitiveness gains for the companies are the increased security of supply for the companies, lower carbon costs and associated risks, brand value and marketing of green products. For society cost savings can be achieved due to the lower required capacity for infrastructure.

#### 6.1.1.3 Programming

The programming consists of three demonstration projects at different scales. To enable effective transfer of the insights gathered in these projects there is an additional research programme that aims to develop tools and guidelines. These will enable other companies to also integrate renewables in their installations.

- **4 x Small scale demo** (order of magnitude 10 MW) – this will demonstrate the possibility of integrated process industry with dedicated renewable energy generation and including piloting of certain technologies in industrial applications. For example, solar heat for drying in ceramics and cement.
- **2 x Medium scale demo** (order of magnitude 100 MW) - this will demonstrate the possibility of integrated process industry with dedicated renewable energy generation at

larger volumes and integrating multiple technologies, such as storage. For example, solar heat and PV for cement or PV connected to non-ferrous.
- **1 x Large scale demo** (order of magnitude 1,000 MW) – this will demonstrate. For example, chemical or steel plants with higher level of integration of multiple technologies and more complex demand response.
- **1 x Research programme** that captures the learnings from the demonstration projects to identify best practices and develop guidelines based on the most important success factors. Also, tools will be developed that make it easier for other companies to develop similar integrated sites. The research programme will collect information and make it accessible for developing the small scale, then adapt it for the medium scale, and again for the large scale.

The integrated system and technologies should be designed in such a way that supply and demand are matched as well as possible. Also, the system can be optimised in an integrated way with simulation programmes that simulate the process and combine it with the renewable energy production. The operational optimisation of the system is part of the energy management innovation programme.

#### 6.1.1.4 Investment needs

**Table 3: Investment needs in € million – work in progress and subject to change[13]**

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| 2020-2030 | | | 4x €10 +2x €50 +1x €200 | | €5 | | €345 |
| 2030-2040 | | | | | | | €0 |
| 2040-2050 | | | | | | | €0 |
| Total | €0 | €0 | €340 | €0 | €5 | €0 | €345 |
| *% public funding* | | | | | | | |
| *Public funding* | | | | | | | |

#### 6.1.1.5 Success factors

- Cost reductions in some renewable energy technologies are needed to improve the business case
- Infrastructure is needed to transport the resources to and produced materials from the site (which can be remote, e.g., a Spanish desert)
- Land area availability for certain renewable technologies
- Policy framework that incentivises companies to fully redesign their processes and operations

### 6.1.2 Integration of bio-energy waste and other new fuels

This programme focuses on the increased use of bioenergy and waste in the process industries. Liquid biofuels are scoped out because other higher-value applications exist (e.g. in transport).

Using biomass or waste directly is problematic because of 2 reasons. First, there are several undesired combustion characteristics in biomass and waste. Moisture levels are too high, there are volatiles in the biomass, and there can be contaminants in the biomass or waste. The desired characteristics depend on the sector. For example, the cement sector is relatively tolerant and already uses biomass, refuse derived fuel, animal meal, and sewage sludge, whereas in the

[13] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

ceramics sector the contaminants would affect the product quality. In the steel sector there are possibilities, but pre-treatment is required, and the processes are rather sensitive to properties of the bio-coke.

The second problem is that the streams of biomass or waste can fluctuate significantly in terms of their composition. The processes in the process industries are often not capable of dealing with this fluctuation.

The challenges for this innovation programme can be overcome either by

a) **Biomass-tolerant processes** - Developing processes that are more tolerant to the combustion characteristics and fluctuation in composition in the biomass
b) **Biomass pre-treatment** - Developing pre-treatment technologies that convert the biomass to a fuel with consistent characteristics that are equal to the currently used fossil fuels

**Text box 3 - Bioenergy controversy**

There is a debate about the sustainability issues surrounding bioenergy. For example, there are concerns around competition of bioenergy with food, causing food prices to increase. Also, there are concerns related to carbon sinks and (indirect) land use change. Although such concerns should be taken seriously and care should be taken to avoid adverse effects, for this innovation programme we do not address these issues. Instead, we assume that effective regulations will be in place that ensure that all biomass used is sustainable.

Biomass availability is limited in the EU. Although biomass import is common, there are also sustainability concerns related to this imported biomass. At the same time, other sectors such as transport, the built environment or the power sector can use the available biomass to meet their energy needs (even though biofuels are scoped out for this programme for that reason). As a result, it is unlikely that biomass can serve as a silver bullet to replace all industrial fossil fuel consumption. For simplicity, we do not take this into account in the programme, although we do present a range when it comes to the impact of this programme.

### 6.1.2.1 Innovation objectives

- Demonstrate the direct use of biomass in new industrial applications (two demos in 2025)
- Solid bioenergy available at energy density of 20 $GJ/m^3$ (i.e., that of coal) in 2025
- Cost-effective integration of biomass in industrial applications

### 6.1.2.2 Impacts

***GHG emissions***

In theory all fossil fuels can be replaced by bioenergy and waste if all barriers are overcome. This would mean that the current direct emissions of all process industries would be mitigated. That amounts to around 505 MtCO2. In the case of waste, this can only be achieved with biogenic waste, otherwise the $CO_2$ emissions would remain fossil.

However, considering the limited availability of biomass, this potential will not fully be achieved. As a minimum, the existing new policies scenario from IEA can be taken. This scenario projects the energy system under current and planned policies, and therefore can be considered a business-as-usual scenario. According to this scenario biomass accounts for 13% of industrial energy demand in 2040 (IEA, 2018). Today this is 10%. This means that 3% of industrial energy demand is fossil energy that is displaced by bioenergy. This 3% equates to 6% of the fossil fuel share of energy supply (i.e. 50%) in 2017, and this implies a 6% reduction in GHG emissions. If this percentage is also applicable to the process industries, the reduction would be 6% of the 505 MtCO2 direct emissions today; i.e. 30 $MtCO_2$.

In practice the impact will be in between these two estimations. In the IEA's sustainable development scenario, the contribution of bioenergy is about three times larger than in the new policies scenario (15% of industrial energy demand), and this implies around 90 $MtCO_2$ reduction (IEA, 2018).

Note that this simplified estimation does not fully account for the difference between process emissions, and only considers combustion emissions. If the biomass would otherwise be landfilled there are additional GHG reductions from anaerobic digestion on landfills. If the biomass would be composted, then half of the carbon is turned into CO2.

***Waste***

If waste streams are used as a fuel in industry, then it will reduce landfilling. Today about 90 Mt of organic waste is landfilled in Europe from municipal solid waste alone (including food, wood and garden waste). If this is used by the process industries instead the landfilling will be avoided.

***Competitiveness***

The competitiveness of bioenergy or waste with fossil fuels depends on the pre-treatment. The below table shows how at a carbon price of €25/$tCO_2$ bioenergy is competitive at €10.8/GJ. As this includes the costs of the biomass and the costs of the pre-treatment, these are the key factors. The cost of pre-treatment may be reduced by this innovation programme, and the cost of biomass is also dependent on market dynamics, such as the demand for biomass in other sectors.

| Parameter | Current technology | 2050 technology |
|---|---|---|
| **Emissions** ($tCO_2$/GJ heat production) | 0.056 | 0 |
| **Carbon price** (€/$tCO_2$) | 25 | 25 |
| **Energy price** (€/GJ) | 9.4 (natural gas) | 10.8 (break even biomethane price) |
| **Total cost** (€/GJ heat) | **10.8** | **10.8** |

Biomass-tolerant processes will be more cost-effective and therefore increase competitiveness further if they develop to TRL9 (if they are not more cost-effective, they will not be fully developed, and the pre-treatment option will only be used instead).

### 6.1.2.3 Programming

Since it is uncertain which option will be most cost-effective, the innovation programme investigates both options.

**Biomass-tolerant processes**

There are only a few processes that currently can tolerate biomass without pre-treatment (e.g., cement kilns), and it is still unknown for which processes such biomass-tolerant alternative processes are available.

Additionally, using biomass directly in the process will need to be integrated into the process. It will impact the logistics and energy storage on-site because biomass has a lower energy density than fossil fuels. The fluctuating composition might need to be measured real-time in order to adjust the process accordingly. Flue gases would be different, which might require flue gas cleaning. Burners might need to be optimised for the bioenergy source. Also, of course the product quality should be monitored closely.

In areas with low potential for renewable power generation, the biomass might also be used in an on-site combined heat and power plant.

To develop the new processes that are biomass-tolerant first six parallel research tracks of €2 million each are executed, then four pilots of €5 million each and later two demonstration projects of €25 million each.

**Biomass pre-treatment**

The pre-treatment technologies are further developed. Such technologies for solid biomass include mechanical processing, drying, palletisation, steaming, pyrolysis, and torrefaction. Biogas can be upgraded to biomethane, which has the same characteristics as natural gas. A pure fuel could enable pure $CO_2$ and therefore make capture and reuse of the carbon more cost-effective.

For example, blast furnaces today use huge amounts of coal in two types: injectable PCI-coal, and coke charged in the blast furnace. The PCI-coal is easier to replace by biomass, but the coke (higher volumes) is more difficult to replace by bio-coal.

Also, symbiosis between process industries and the pre-treatment of biomass could achieve synergies, for example by using waste heat to dry the biomass. This topic is included under innovation programme (6.13.2 Community of Practice)

To develop this option 2 pilots of €5 million each are programmed to test each solid bioenergy option (this can be in the order of magnitude for example 10 kW-100 kW or potentially smaller for decentralised applications). Then, two demonstration projects of €25 million each where the solid bioenergy option is used at scale and integrated in the process (this can be in the order of magnitude for example 1 MW-10 MW or smaller in the case of decentralised applications).

#### 6.1.2.4 Investment needs

**Table 4: Investment needs in € million – work in progress and subject to change**[14]

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| 2020-2030 | 6x €2 | 6x €5 | 2x €25 | | | | €92 |
| 2030-2040 | | | | 2x €25 | | | €50 |
| Total | €12 | €30 | €50 | €50 | €0 | €0 | €142 |
| *% public funding* | | | | | | | |
| *Public funding* | | | | | | | |

#### 6.1.2.5 Success factors

- Close collaboration with energy sector needed
- Availability of biomass, including sustainable logistics
- Relation to industrial symbiosis – re-using waste heat for drying in pre-treatment

### 6.1.3 Competitive hybrid transition to low-carbon industrial energy supply

Whereas the other innovation programmes in this innovation area focus on a switch from fuel to renewables, this innovation programme aims to enable a competitive transition towards these renewable energy options.

Going to fully renewably powered process industries in 2050 requires a transition, and in the first decade renewable energy supply might not be able to supply industrial demand. Also, the energy infrastructure might not be available yet to provide the volumes of renewable energy. Therefore, it is more reliable and cost-effective to work with hybrid installations that run on a mix of fossil and renewable energy sources, and with the capability to increase or decrease the share of renewable energy based on the availability.

Some hybrid systems are already available (for example hybrid boilers that run on natural gas and/or electricity). However, these systems have not been demonstrated at full industrial scale yet. For other combinations (e.g. hybrid ceramic kilns or hybrid reduction processes), new hybrid combustion technologies need to be developed and/or demonstrated to allow the process industries to implement them.

[14] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

#### 6.1.3.1 Innovation objectives

The objective of this innovation programme is to demonstrate hybrid technologies that use less than 1/3 of fossil-based energy carriers and at least two-thirds hydrogen, electricity, or biogas by 2030 without negatively affecting productivity.

#### 6.1.3.2 Impacts

***GHG emissions***

This programme mainly has an impact on the medium-term. It enables the faster penetration of renewable energy in the fuel mix of the process industries. Therefore, the impact in 2030 is assessed here instead of in 2050.

Hybrid technologies target fossil fuels that are used for heating and reduction processes. This amounts to around 30% of emissions in the process industry. Of these emissions, two-thirds are replaced by renewable energy. This implies a total reduction equal to 30% of process industry GHG emissions in 2030.

Note that this represents the technical potential if all installations are replaced/retrofitted with hybrid systems. It is unlikely that all companies will use these transition technologies, because the technologies might not be strategic if there are plans for a fully renewable installation in the next investment cycle.

***Competitiveness***

The competitiveness of the hybrid boiler is taken here as a simple example to illustrate the impact on competitiveness. The CAPEX is assumed to be similar. The table shows that the electricity should be available at an electricity price of €18.4/GJ or lower to be competitive. Note that this is the average electricity price during the 2/3 of the time that electricity is used. As electricity prices fluctuate, the cheapest 2/3 of electricity are replacing the fossil fuels.

| Parameter | Current technology | 2050 technology |
|---|---|---|
| **CAPEX** (€/GJ heat production/year) | 0.5 | 0.5 |
| **Capital recovery factor** | 11% (i=10%; L=25yr) | 11% (i=10%; L=25yr) |
| **Emissions** (tCO2/GJ heat production) | 0.056 | 0.056 * 1/3 |
| **Carbon price** (€/tCO2) | 25 | 25 |
| **Energy consumption** (GJ) | 1 | 1 |
| **Energy price** (€/GJ) | 9.4 (natural gas) | 1/3 * 9.4 (natural gas)<br>2/3 * 12.4 (break even electricity price) |
| **Total cost** (€/GJ heat) | **11.9** | **11.9** |

Additionally, there is value in the reliability of availability of energy. Because there are two options, production is not affected if supply of one option is disrupted. Also, this results in a reduction of fossil fuel imports and therefore increases energy security for Europe.

#### 6.1.3.3 Programming

The programme includes the scale up of hybrid technologies

- **Upscaling of hybrid technologies** – Some technologies are readily available, but not at the required scale. Therefore, the technologies should be demonstrated in an industrial application. Also, key parameters should be explored (e.g. flame properties, fume volume, interaction with the process). Two demonstration programmes are programmed: one for a high-pressure system and one for a low-pressure system. The demonstration projects will be finished in 2025 and will require €20 million each.
- **Integration of hybrid technologies** – Some technologies are still under development. For example, hybrid ceramic kilns require the demonstration of electric kilns first (see innovation programme 6.4.2 Other electricity-based heating processes). After that development, this integration of conventional fossil and renewable technologies also requires demonstration at large scale. These are more complex processes and therefore

also require more advanced digital technologies to ensure the quality of the product. Costs of two demonstration projects are estimated at €30 million each.

#### 6.1.3.4 Investment needs

**Table 5: Investment needs in € million – work in progress and subject to change**[15]

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| **2020-2030** | | | 2x €20 | | | | €40 |
| **2030-2040** | | | | 2x €30 | | | €60 |
| **2040-2050** | | | | | | | |
| **Total** | €0 | €0 | €40 | €60 | €0 | €0 | €100 |
| ***% public funding*** | | | | | | | |
| ***Public funding*** | | | | | | | |

#### 6.1.3.5 Success factors

- Competitively priced renewable energy for at least 2/3 of the time is necessary, as companies will use the cheapest energy source at that point in time
- Infrastructure that can transmit the renewable energy is key. If insufficient grid capacity is available to supply the energy needs of the installation, it will likely not be economic.

[15] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## 6.2 Enhancing energy flexibility and diversity

### 6.2.1 Flexibility and demand response

This innovation programme focuses on options within the process industries to adapt to the fluctuations in energy supply caused by the increased penetration of variable energy sources.

Process industries have the option to consume less energy when less energy is available (and prices are high) or to consume more energy when a surplus of energy is available (and prices are low or even negative). Consuming less can be done by producing slower or less, or by taking energy from storage. Consuming more can be done by producing more (producing faster or producing more intermediates if there is excess production capacity and storing them), or by putting energy in storage.

*<< Trimet Aluminium project description from Al Sample Vision 2050 will be added to illustrate >>*

To leverage the existing flexibility in the process industries, companies need to understand the potential and implement digital process control systems that are optimising the process whilst also taking the value of flexibility into account. Additionally, processes can be (partially) redesigned or modified to account for increased flexibility. On-site storage in the form of product (or intermediates), electricity, heat, or other energy vectors can further increase the flexibility of an installation. Finally, new production processes can be developed that allow for a very fast response rate (i.e. they can ramp up or down production fast).

#### 6.2.1.1 Innovation objectives

- Substantial increase in flexibility of the process industries
- Increase response rate of flexibility

#### 6.2.1.2 Impacts

***GHG emissions***

Flexibility and demand response in process industries enables the process industries to use the energy that would otherwise be lost (since there is no other use for it). The materials produced with this excess power displace materials produced with fossil energy sources, and therefore fossil energy consumption is reduced. However, because the development of power systems in Europe is difficult to predict, the extent of this impact is unclear. It is estimated to be between 1% and 10% of SPIRE-CCNI sector emissions.

***Competitiveness***

The key impact of flexibility and demand response on competitiveness is the creation of additional revenue streams for industry. The size of the revenues depends on the flexibility market that is addressed (e.g. balancing market or ancillary services) and the local circumstances and capacity of the grid.

Additionally, the stabilising effect on the gird enables higher penetration of renewables and reduces the costs of the energy system as the grid requires less capacity.

#### 6.2.1.3 Programming

- **Explore potential flexibility in existing processes** – This can be for example running chemical processes at somewhat higher temperatures leading to faster production. Currently flexibility is not yet considered in the process control systems, so these digital tools need to be developed, adapted or redesigned (link with innovation programme 6.16.1 Optimised plant operations control towards highest quality products and fully energy, resource efficient and environmentally friendly plants). Eight demonstration projects are foreseen in different regions and sectors. This broad demonstration enables to analyse the potential in under different circumstances. Expected investment need is €2 million per demo on average.

- **Redesign processes to enable more flexibility** – When companies have already mapped the opportunities for flexibility, the next step of flexibility is to change the process to allow for more flexibility. If a bottleneck exists in the process that limits flexibility, the removal of the bottleneck can deliver more flexibility and associated revenues. This should be demonstrated in 4 demonstration projects of €5 million each.
- **Add flexibility by means of storage** – In some cases on-site storage can be more cost-effective than centralised storage in the energy system. For example, industrial sites with integrated renewables can use more of the generated electricity or waste heat can be utilised later in time in batch processes to bridge the time between batches. This storage can be in the form of electricity, heat, or other energy vectors. For each storage option one demonstration project is programmed: Three projects of €20 million each.
- **New processes with faster response rate** – The potential for flexibility can be further stretched by exploring new processes that are able to ramp up very fast and then down again. Such new technologies would not run at full capacity, but only during times when electricity is cheap. Therefore, efficiency of the process is less important than for process that run continuously. Existing low-TRL processes will be developed and piloted. Three pilots are foreseen and depending on the results (and the market for flexibility) these can be demonstrated. An evaluation should take place in 2024. The three pilots are estimated to require €10 million investment each.

### 6.2.1.4 Investment needs

**Table 6: Investment needs in € million – work in progress and subject to change[16]**

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| **2020-2030** | | 3x €10 | 8x €2<br>2x €5 | 3x €20 | | | €116 |
| **2030-2040** | | | | 2x €5 | | | €10 |
| **2040-2050** | | | | | | | |
| **Total** | €0 | €30 | €26 | €70 | €0 | €0 | €126 |
| ***% public funding*** | | | | | | | |
| ***Public funding*** | | | | | | | |

### 6.2.1.5 Success factors

- Infrastructure should be available for heat and electricity in order to enable process industries to utilise the supply peaks
- Cost reductions in storage technologies (e.g., batteries) is key to create a feasible business case for on-site storage
- Transmission system operators (TSOs) willing to pay for flexibility. TSOs can avoid increasing grid capacity because of increased flexibility at the demand side. This can very much differ per location.

[16] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## 6.3 Enhanced utilisation of different grades of heat

### 6.3.1 Heat exchange optimisation

*<<this innovation programme will be described in the next version and will cover*

- *optimisation of heat use/exchange across boundaries of the own plant/sector,*
- *the potentially required technological developments (heat exchangers) to enable this, and*
- *technologies to convert residual heat to useful forms of energy, including covering the water – energy nexus (exploiting the opportunity on waste heat from waste water) >>*

## 6.4 Electrification of heating processes

### 6.4.1 Electricity to upgrade waste heat

Heat pumps have the capacity to use some electricity to produce more useful heat at a higher temperature from waste heat.

Currently (compression) heat pumps are commercially available which can deliver heat up 100°C. Research is devoted to increasing the temperature of the delivered heat. Some systems are available capable to deliver temperatures of 150 °C. However, no commercial systems are available in what is indicated as the medium or intermediate temperature heat pump. Important challenge in this range is to reduce the capital investment cost to become competitive.

Although the compression heat pump can potentially be developed for temperatures up to 250°C, for high temperature heat pumps (>250°C) a range of other principles is considered (e.g. based on adsorption/desorption, thermoacoustic, etc.). However, these developments are in general at low TRL (laboratory research, functional models, proof of concept: TRL3-4).

Vapour recompression is another technology to convert electricity efficiently into heat where the heat pump is integrated in the process and uses the process flow as working medium. Especially interesting to upgrade the quality of steam, currently systems for compression to 150°C are available. Development focuses on introducing vapour recompression systems working at 180°C as this would enable production of widely used 10 bar steam. Although cost effective equipment is available for large scale (>>10 MW), development of cost-effective systems in the MW scale is a key objective.

One of the issues when integrating heat pumps into existing processes is the cost of integration. Especially if additional infrastructure needs to be built, the business case becomes challenging. An effective manner of integrating heat pumps is so-called “process-integration” of heat pumps, meaning the heat pump is not part of the general utilities, but integrated in a specific process, using waste heat from the process to provide heat. An example is the use of a heat pump in combination with a distillation column using heat from the condenser to feed the reboiler.

This innovation programme focuses on the widespread adoption of heat pumps for industrial heating, including mechanical vapour recompression.

#### 6.4.1.1 Innovation objectives

The innovation challenges differ for different temperature levels:

- For temperatures up to 150°C the technology is already available, but too expensive to compete with fossil fuels;
- For higher temperatures, the technology is not yet developed and there are various technical challenges that need to be solved. Technologies with the potential to reach temperatures up to 250°C are currently in the early stages of development. This is needed because a large share of heat demand in energy intensive industries is at higher temperatures (de Smidt & Marina, 2017);
- It might be possible to use heat pumps also for even higher temperatures up to 350°C, but the feasibility of this is uncertain;

Temperatures above 350 °C are unlikely to be feasible because the efficiency reduces with higher temperature differences and with lower efficiency other electric heating options (see the next innovation programme) are more interesting than upgrading heat with a heat pump.

The innovation objectives are:

- **Reduce CAPEX of heat pumps up to 150°C to 200 €/$W_{th}$ in 2025 and (market driven) 150 €/$W_{th}$ in 2050**: Because of their high efficiency heat pumps can compete on fuel costs with fossil fuels even if the electricity price is much higher than the price of fossil fuels. Operating at a coefficient-of-performance of 3 for example, a heat pump will be competitive on energy cost even if the cost electricity is three times as high as the cost of the fossil fuel. However, the high upfront investment cost of current heat pumps leads to unattractive pay-back times. Therefore, large-scale deployment of heat pumps requires a reduction of the CAPEX. The 2030 target will trigger the first wave of heat pump deployment and afterwards the standardisation and supply chain optimisation will decrease costs further to meet the 2050 target;

- **Developing heat pumps and MVR up to 250°C to TRL 9 in 2030** – Several innovations are necessary to extend the temperature operating range of compression heat pumps: availability of refrigerants with good thermophysical properties and low global warming potential (e.g. HFO's ), suitable lubricants to ensure a correct operation of the lubricant-refrigerant mixture within the operating temperatures, compressor technology and suitable vapour compression cycle, components able to withstand high temperatures, and novel concepts and cycles;
- **Developing heat pumps and MVR up to 350°C to TRL 9 in 2040** - Potentially it is possible to push heat pumps up to even higher temperatures. This will first be researched further until 2030 and at a later stage will be decided whether this is worth pursuing further.
- **Cost-effective integration of heat pumps in processes** - Much of the heat used in industry is supplied by generic utility systems. In the case of fossil fuelled systems, the temperature of heat does not impact the efficiency of heat production. In the case of heat pumps the efficiency depends on waste heat temperature levels and temperature of produced heat. As a result, highly process-integrated solutions offer better opportunities to increase efficiency and reduce investment cost. To capitalise on the opportunities, it is necessary to involve process and equipment suppliers in the development of process integrated heat pump systems. Projects aimed at knowledge transfer to the engineering sector and technology providers require funding. Engineering firms are not well-enough informed about the potential and possibilities for heat pumps integration because the market is not asking for it. Therefore, demonstration projects are required.
- **Knowledge and awareness about heat pumps –** A major barrier for heat pump implementation in industry is the lack of knowledge about the integration of medium- and high-temperature heat pumps in industrial processes. Also, there is a low level of awareness of the technical possibilities and the economically feasible application potentials among users, consultants, investors, plant designers, producers and installers. Therefore, sharing of knowledge and creating awareness is key to the success of the innovations in this programme.

#### 6.4.1.2 Impacts

In most SPIRE-CCNI sectors a substantial part of the $CO_2$ emissions is associated with heat production (e.g. furnaces, steam production). Switching from fossil fuels to renewable electricity as energy carrier for heat production will reduce these $CO_2$ emissions to almost zero.

***GHG emissions:***

| **Sector** | **Current Emissions in EU,** MtCO2e | **Emissions targeted by the IP[17], %** | **Reduction within targeted emissions,** % | **Emission reduction impact,** MtCO2e |
|---|---|---|---|---|
| Cement | 105 | N/A | 100% | 0 |
| Steel | 190 | 0-10% | 100% | 9.5 |

[17] The steel process currently produces high amounts of waste heat, in the future this might change; cement and ceramics need higher temperatures than can be delivered by this innovation programme; water does not have many heat-based processes (if any).

| | | | | |
|---|---|---|---|---|
| Chemicals | 128.4 | 15%[18] | 100% | 19.3 |
| Ceramics | 17 | 0 | 100% | 0 |
| Non-ferrous metals | 17.8 | 30% of heat related emissions[19] | 100% | N/A |
| Minerals | 19.4 | N/A | 100% | 0 |
| Water | 27 | N/A | 100% | 0 |
| **Total SPIRE-CCNI** | **505** | **6%** | **100%** | **28.8** |

Besides these sectors there can be impacts in the pulp and paper and food industry as a result of reduced costs of heat pumps until 150°C.

As more options will be targeting the industrial heat emissions, the actual impact of heat pumps will likely be lower. For example, in the amount of waste heat available will decrease in the fertiliser industry when it would switch towards using green hydrogen.

***Competitiveness***

Heat pumps would primarily displace gas boilers. The below calculation shows that compared to a typical gas boiler, the 2050 heat pump would be competitive even at an electricity price of €40 per GJ. That is substantially higher than our projected industrial electricity price in 2050 (around €16/GJ; see Annex D: Energy and carbon price assumptions).

| Parameter | Current technology | 2050 technology |
|---|---|---|
| **CAPEX** (€/GJ heat production/year) | 0.03 | 0.3 |
| **Capital recovery factor** | 11% (i=10%; L=25yr) | 11% (i=10%; L=25yr) |
| **Emissions** (tCO2/GJ heat production) | 0.056 | 0 |
| **Carbon price** (€/tCO2) | 25 | 25 |
| **Energy consumption** (GJ energy input/GJ heat output) | 1.1 | 0.3 |
| **Energy price** (€/GJ) | 9.4 (natural gas) | 40 (break even electricity price) |
| **Total cost[20]** (€/GJ heat) | **12** | **12** |

### 6.4.1.3 Programming

Reduction of cost requires development of the supply chain (i.e. development of components such as compressors and working fluid). But an essential step to be taken by potential suppliers is also (further) standardise solutions. Studies have shown standardisation for 2-5 $MW_{th}$ offers the greatest potential for wide-scale implementation. To achieve the cost target development of (cost) optimised solutions and demonstration projects in a broad range of applications are necessary. Cooperation with non-SPIRE-CCNI sectors, such as Food, Pulp and Paper are important. To stimulate the market uptake for heat pumps, a study on market potential and a project on developing new business models.

Another technology which offers great potential for 2030 is vapour recompression. Where components are currently available to upgrade steam to 120-150°C, the ambition should be to go to 250 °C (the new normal in 2050). For 2030 development of novel (axial, centrifugal) compressor technology enabling 180°C.



[18] Estimate on basis of heat demand distribution for the Dutch chemical industry compiled by ECN/TNO (Nationaal Expertise Centrum Warmte, 2013), not accounting for the effect of heat cascading.
[19] This is the heat use up to 350°C.
[20] Only energy costs and CAPEX for heat generating equipment are considered, others are excluded

Use of heat pumps for higher temperatures (>250°C…350°C) require novel concepts and cycles such as adsorption and thermoacoustic heat pumps.

Most investments need to be made before 2030 because most technologies are already developed quite far:

1. **Demonstration projects non-integrated heat pump below 150 °C** – first retrofitting solutions at least 2 large ones (2021). They need to address multiple applications. This will trigger more learning. Supply chain needs to be involved (compressor manufacturer, heat pump supplier, multiple end users). Engineering should be involved as well as a partner. As soon as possible (first call in programme). Two projects * €20 million = €40 million.
2. **Demonstration process integrated heat pump below 150 °C** – integration of solutions in processes (like distillation units, or dryer systems – sold as a package and redesigning the process equipment – for example the sizing of the heat exchangers) for a couple of typical applications. Demonstrating the benefit of process integration. Together with digitalisation to develop tools (advanced process modelling). Five projects * €8 million = €40 million (2025).
3. **Coordinated support action on market potential** – market study including dissemination activities, also addressing potential and barriers (in the first call) involving engineering firms and all other relevant actors. Support for national implementation programmes to cope with differences in regulations and market organisations. Update this study later (start immediately; depending on situation in 2024). €1 million per study * two studies = € 2 million.
4. **Coordinated support action on business models** – Investigating and developing new business models. Potentially together with other sectors (energy, financial services). (start immediately - first call). Including workshops, ideation, conferences, etc. €1 million.
5. **Research action heat pumps until 250 °C** - From TRL 3-4 to 5 in 2021-2025 – research and development, some lab scale of 4 technologies. R&D for four technologies * €5 million = €20 million
6. **Piloting heat pumps until 250 °C** – from TRL five to seven piloting for selected technology. One pilot of €10 million. (2026-2030)
7. **Demonstration heat pumps until 250 °C** - from TRL seven to nine in 2035 – demonstration €20 million. This also assumes that supply chain partners are supported additionally
8. **Research action heat pumps until 350 °C** – to TRL four to five in 2030 so we can decide then whether it can become competitive. If so, further development until TRL9 in 2040. This is possible more rapidly due to lessons learned from lower temperatures. R&D for three technologies * €5 million = €15 million. If successful a pilot and demo between 2030-2040;
9. **Piloting heat pumps until 350 °C** – from TRL five to seven piloting for selected technology. One pilot of €10 million. (2030 - 2035)
10. **Demonstration heat pumps until 350 °C** - from TRL seven to nine in 2040 – demonstration €20 million. This also assumes that supply chain partners are supported additionally

### 6.4.1.4 Investment needs

**Table 7: Investment needs in € million – work in progress and subject to change**[21]

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment (FID) | Total |
|---|---|---|---|---|---|---|---|
| **2020-2030** | | 4* €5 +3* €5 | €10 | 2x €20 +5x €8 | 2* €1+ €1 | | €128 |

[21] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment (FID) | Total |
|---|---|---|---|---|---|---|---|
| **2030-2040** | | | €10 | €20 +€20 | | | €50 |
| **2040-2050** | | | | | | | €0 |
| **Total** | €0 | €35 | €20 | €120 | €3 | €0 | €178 |
| ***% public funding*** | | | | | | | |
| ***Public funding*** | | | | | | | |

#### 6.4.1.5 Success factors

- **Sufficient affordable renewable electricity**. Introduction of large amounts of renewable electricity system requires changes to the regulation and organisation of the electricity grid and markets. This offers opportunities for novel stakeholders and business models.
- **Supportive policy framework.** In particular a need for financing instruments that support the implementation in the transition phase when CAPEX are not yet low enough to enable a business case.
- **Financial instruments for SMEs so the supply chain can develop.** Cost reduction can be achieved through technology development, but standardisation and supply chain development are equally important. Large-scale demonstration projects should give the market (heat pump suppliers, component suppliers) enough confidence in the emerging market to develop. As these suppliers are largely SME's, dedicated instruments to support these investments should be available.
- **Connection with flexibility innovation programme.** Flexibility of demand (demand response) represents a monetary value but requires development of business models and formation of markets to capitalise.

### 6.4.2 Other electricity-based heating processes

#### 6.4.2.1 Innovation objectives

This innovation programme addresses heating up to temperatures above 350°C, where heat pumps are not expected to play a role.

A wide range of technologies, such as microwave heating, infrared, inductive heating is used within other sectors such as Pulp and Paper and Food. However, these technologies find very limited application within SPIRE-CCNI sectors where cost of energy is a more important part of the product cost. Other technologies such as microwave heating, plasma technology, etc. are still at low TRL level for application in the SPIRE-CCNI sectors. A high degree of electrification of the industry implies the potential of these technologies need to be fully utilised in the SPIRE-CCNI sectors.

This innovation programme focuses on electrical furnaces delivering temperatures of 800°C or higher, for example cement kilns, steam methane reformers, ceramic furnaces.

In some of these cases transformation of the process from fossil-fuelled to electrically driven will translate into a one-on-one replacement of the energy source without mayor changes to the process side. In that case the heating technology can be considered a "retrofit" in an existing process. In these cases, the business case relies strongly on the cost of electricity vs the cost of fossil fuels and $CO_2$ pricing.

However, in many cases replacing the fossil heat source by an electrical heat source opens novel options in the design of the process itself. This brings possibilities to create a competitive process, for example because the integration of electrical heating and novel process is more efficient than the fossil-fuelled alternative. The roadmap for the Australian industry (Beyond Zero Emissions, 2018) gives examples of a number of such applications: effective/efficient include inductive melting (steel, non-ferrous), drying processes in the chemical industry, drying in the ceramics industry. However, it does also mean development of novel processes.

Therefore, for the programming a distinction is made between processes which:

- Just heat the process streams with electricity rather than with fossil fuels ("no efficiency gains in the process side").
- Heat the process streams electrically with a different mechanism that also deliver efficiency gains in the process but required redesign of the process.

These variants, and their applicability for the various sectors, are shown in the table below.

| Efficiency gains | Based on existing process: | Requiring process redesign: |
|---|---|---|
| **No efficiency gains in the process side** | *2030-2040:*<br>• Ceramics furnace;<br>• Reforming. | *2021-2040:*<br>• Electric cracking;<br>• Lime furnace;<br>• Cement furnace; |
| **Efficiency gains in the process side** | | *2021-2035:*<br>• Ceramics (drying techniques, e.g. MW);<br>• Inductive melting. |

The overarching objective of this innovation programme is to demonstrate (TRL 9) electrical heating at high temperatures and using advanced heating technologies before 2040 for all applications, more specifically:

- For the applications with limited efficiency gains: Develop and demonstrate these technologies, with an emphasis on reducing CAPEX.
- For the process-options: Develop the technologies in such a manner that the energy efficiency gains are realised.[22]

*Electric boilers are described in Innovation Programme "Competitive hybrid transition to low-carbon industrial energy supply".*

### 6.4.2.2 Impacts

*<< Note that it is not clear yet whether electrical kilns can be used in the cement/lime sector. >>*

In most SPIRE-CCNI sectors a substantial part of the $CO_2$ emissions is associated with heat production (e.g., furnaces, steam production). Switching from fossil fuels to renewable electricity as energy carrier for heat production will reduce these $CO_2$ emissions to almost zero.

***GHG emissions***

| Sector | Current Emissions in EU, MtCO2e | Emissions targeted by the IP, % | Reduction within targeted emissions, % | Emission reduction impact, MtCO2e |
|---|---|---|---|---|
| Cement | | ±33% | 100% | |
| Steel | | Potentially in the steel glowing and rolling, not quantified | 100% | |
| Chemicals | | ±20% | 100% | |
| Ceramics | | Max 80% | 100% | |
| Non-ferrous metals | | | 100% | |
| Minerals | | Lime sector: ±33% | 100% | |
| Water | | N/A | 100% | |

[22] The assumption here is that the CAPEX is less critical for these technologies, as they also deliver efficiency gains.

| | | | | |
|---|---|---|---|---|
| **Total SPIRE-CCNI** | | | | |

***Waste:***

No formation of waste is prevented.

However, in some sectors currently waste flows are used as fuel, which would be replaced by using electrical furnaces – leading to a need to process that waste:

- **Cement** – currently uses a big variety of waste (solid and liquid) to fuel kilns --> needs to be processed using the variety of recycling options discussed in the rest of this document.
- **Lime** – currently uses solid waste and spent solvent to fuel kilns --> --> needs to be processed using the variety of recycling options discussed in the rest of this document.
- **Chemicals** – crackers: the current outlet for combustible waste gases (the furnaces) is no longer available --> addressed in Innovation Programme, "Electrically-driven separation."

***Competitiveness:***

Capital costs are not known.

- For the applications where the impact is just a different manner of providing the energy: As there are relevant differences between the efficiencies of furnaces/kilns in different applications (Stork, Meindertsma, Overgaag, & Neelis, 2014), the ratio between electricity required versus fuel replaced might vary as well (and potentially not be 1:1 for all applications). Nevertheless, this option becomes attractive when the electricity price is relatively cheap in comparison with the currently used natural gas/waste.
- The competitiveness of this option increases due to the characteristics of electric heating, for example because of faster processing time or start-up, improved yields or quality, improved control, etc. Again, these impacts are specific for the combination of heating technology and application.

#### 6.4.2.3 Programming

Essentially the innovation projects focus on integral development of the process and the heating technology to come to an optimal solution:

- **Fundamental knowledge** is necessary to understand the fundamentals of the process ("how the brick dries"), optimise processes (drying, sintering, melting) and the advanced heating technologies, and models and methods.
- **Integration of electric** heat solutions in the process development - key to cost-effectiveness; this will require (re-)designing the process to maximise the benefits of novel heating technology and cooperation with equipment suppliers and engineering companies are necessary.

For several applications, the development focuses on just delivering the heat to the kiln electrically. This applies to:

- Ceramics;
- Lime and cement (technology currently at TRL 2-3);
- Reforming (technology currently at TRL 3-4).

In other cases, it is needed to redesign a plant:

- For a cracker (technology currently at TRL 2-3), the heating mechanism and intensity, and the speed of cooling are quite critical;

- For ceramics, there is space for disruptive change (e.g., microwave heating) with efficiency gains.

For advanced electrified heating systems there is a wide range of research topics. There is a range of technologies: resistance heating, inductive heating, microwave heating, ultrasonic plasma heating, radio frequency heating and infrared heating. In such cases, catalysts/reactors might need to be changed too.

Concretely, this means:

- **Electric cracking** and **electric kilns for cement, lime and ceramics** will be developed in 4 stages, delivering TRL 9 in 2040, with **research programmes for enabling topics** laying the foundation.
- Development of **highly flexible electrical heated reactors** at delivering load-flexible reactors at TRL 9 in 2036.
- A programme focussing on **highly efficient electrical heating** for ceramics aims at delivering a more energy efficiency ceramics kiln at TRL 9 in 2040.

*The knowledge about the way materials interact or the way heat is transferred can be leveraged outside of the sector.*

–

### 6.4.2.4 Investment needs

**Table 8: Investment needs in € million – work in progress and subject to change**[23]

| Technology: | Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total: |
|---|---|---|---|---|---|---|---|---|
| **Research on enabling technologies** | 2020-2030 | €20 | 3x €4 | | | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| **Electric heating in ceramics/cement/lime** | 2020-2030 | | 3x €4 (TRL 5) | | | | | |
| | 2030-2040[24] | | | 3x €15 (TRL 7; 2034) | 3x €30 (2040) | | | |
| | 2040-2050 | | | | | | | |
| **Electric cracking** | 2020-2030 | | 4x €10 (TRL 4; 2026) + 2x €20 (TRL 6; 2030) | | | | | |
| | 2030-2040 | | | 1x €30 (TRL 7; 2034) | 1x €200 (2040) | | | |
| | 2040-2050 | | | | | | | |

[23] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.
[24] Could be earlier in case the economical attractiveness of this technology would improve quicker.

| Technology: | Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total: |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| **Flexible Electrically heated reactors** | 2020-2030 | | 3x €4 (TRL 4-5) | | | | | |
| | 2030-2040 | | | 2x €15 (TRL 7; 2030) | 2x €30 (2036) | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Highly efficient electrical heating** | 2020-2030 | | | 3x €10 | | | | |
| | 2030-2040 | | | | 2x €30 (2035) | | | |
| | 2040-2050 | | | | | | | |
| | **TOTAL** | €20 | €116 | €135 | €410 | €0 | €0 | €681 |
| | *% public funding* | | | | | | | |
| | ***Public funding*** | | | | | | | |

### 6.4.2.5 Success factors

- Connection with **flexibility innovation programme**
- Supportive policy framework, aiming at **sufficient affordable renewable electricity**, a **transparent market**.
- **Financial instruments for SMEs so the supply chain can develop**, e.g. regional funding instruments (mainly for the advanced heating technologies, not so much for furnaces).

## 6.5 Electrification to directly drive processes

### 6.5.1 Electrochemical conversion

Fossil fuel is currently used in many sectors in the process industry to drive transformations. Thermal activation is used to drive transformations in the chemical industry, cement industry and minerals. In other cases, the fossil fuel is used directly as a chemical reactant to drive the transformation such as in the case of iron production. These transformations are responsible for a substantial part of the $CO_2$ emissions of the process industry. Different principles can be applied to used electricity, including electrochemical, ionisation and thermal activation.

Developing processes that use “no greenhouse gas emitting electricity” as the driver for the transformation instead of fossil fuels thus significantly reduce GHG emissions. Electrochemistry is emerging as a technology suited for a wider range of molecular transformations across SPIRE-CCNI sectors. In addition to reducing $CO_2$ emissions, other advantages of selecting electrochemical conversion can be the higher selectivity, process flexibility or freedom of choice of in the electrochemical reactor of conditions unattainable in a conventional reactor.

Electrochemical reactors can also play a role in energy storage for the renewable fluctuating energy production. Applications with the earliest business cases may lie primarily in the chemical industry and the steel industry. But electrochemical conversions of interest to the Cement sector are also under investigation, albeit at a low TRL level.

Different types of electrochemical reactors are being developed where the most important distinction is between the low temperature, largely aqueous based. The existing chlor-alkali electrolyser is an example of this type. High temperature electrochemical reactors can convert $CO_2$ and water into a tuneable syngas directly. Where carbon containing reactants (like $CO_2$, or carbon from non-fossil origin is (biomass, air capture) or when the carbon is recycled to the process, the carbon loop can be closed. High temperature electrochemical reactors can also be used other oxidation processes, such as ethylene from natural gas and propane oxidation although these applications are currently at low TRL.

Improvements in the electrochemical process are necessary. For low temperature electrolyser key challenges include optimisation of the design of electrodes, innovative electrolyte and electrode systems to enable novel transformations (circumvent limits resulting from current electrode materials). Key parameters to optimise include the current density, Faradaic efficiency, electrode lifetime, overpotential. At the same time the use of scarce materials (e.g., Iridium) or toxic materials (mercury, lead) needs to be minimised. The cost of electrodes can be significantly reduced by developing cheaper catalysts.

For high temperature electrochemical reactors material issues (durability, performance) and scale-up of manufacturability and reactor design are key innovation area.

It is likely that a several of the currently broad range of molecules targeted for electrochemical reduction of $CO_2$ will play a role in 2050. The difficulty is to determine at the current time which are the promising routes and molecules. It is necessary to develop insight into potential through broad exploration of electrochemical processes, including impact analyses (environment, climate, market, etc.), and techno-economic analysis (TEA). In particular it is necessary to understand how the different possible molecules will fit the future energy infrastructure and sustainable industry.

#### 6.5.1.1 Innovation objectives

For electrochemical conversions, three distinguished innovation objectives are identified:

- **Development of electrochemical processes to create high added value chemicals at low temperatures:** For more complex molecules electrochemistry is tuned to produce efficiently a wide range of specialty chemicals efficiently and with high selectivity. The objective is to develop a class of reactors capable opening the way to producing a broad range of materials electrochemically are low temperature, aqueous based reactors. Important applications lie in the conversion of waste streams, bio-based platform chemicals and $CO_2$ into high value products, like for example electrochemical conversion of $CO_2$ to formic acid, hydroxy methyl furfural (HMF) to furandicarboxylic acid (FDCA) and hydrogen peroxide.

- **High temperature electrochemical reactors for syngas and chemicals:** High temperature co-electrolysis is an emerging technology with the potential to (key illustrative examples):
  - Replace natural gas as the energy and feedstock for syngas[25]/CO production or using water and $CO_2$ as feedstock;
  - Produce ammonia electrochemically from water and nitrogen;
  - Produce ethylene electrochemically from Oxydative Methane Coupling[26], or from water + $CO_2$;
  - Oxidise propane to acrolein;
  - … new roads using new feedstocks
- **Radical new electrochemical processes to produce non-chemical energy-intensive materials:** Diverse materials such as pig iron, cement and bulk chemicals are produced by thermal activation with high temperature heat as energy input. For most of these processes alternative electrochemical processes are possible. With a few notable exceptions (chlorine production, aluminium) the thermal route has so far been favoured because of the relatively high cost of electricity. In the future process industry, wide availability of renewable energy these processes could radically reduce $CO_2$ by driving the transformation with renewable electricity instead of (fossil-based) heat:
  - Iron oxide which is now converted to **iron** in blast furnaces could also be converted electrochemically – which is covered in Innovation Programme "Integrating renewable energy carriers";
  - The formation reaction towards cement ($CaCO_3$ --> $Ca(OH)_2$) can in principle also be executed electrochemically; the applicability in this sector has not been verified.
  - Non ferrous metals: << *not known, perhaps for Aluminium the inert anode as alternative to the carbon anode* >>.

### 6.5.1.2 Impacts

**GHG:**

| **Sector** | **Current Emissions in EU,** MtCO2e | **Emissions targeted by the IP,** % | **Reduction within targeted emissions,** % | **Emission reduction impact,** MtCO2e |
|---|---|---|---|---|
| Cement | 105 | -33% | | |
| Steel | 190 | . | | |
| Chemicals | 128 | Not yet known | | |
| Ceramics | 17 | | | |
| Non-ferrous metals | 18 | | | |
| Minerals | 19 | | | |
| Water | 27 | 0% | | |

[25] Current use of syngas (hydrogen/ammonia production) will most likely be replaced by alternative hydrogen/ammonia production technologies, however the expectation is that syngas will remain an important platform chemical mixture, as basis for longer hydrocarbon chains (for example with Fischer Tropsch reactions), and as an option to produce methanol (and DME).

[26] Oxidative methane coupling could lead to 100% GHG emission reduction when biogas would be used.

| | | | | |
|---|---|---|---|---|
| **Total SPIRE-CCNI** | **505** | | | |

**Waste:**

No impact on waste production.

**Competitiveness:**

The competitiveness depends significantly on the costs for renewable electricity and on the applications.

#### 6.5.1.3 Programming

To achieve large-scale implementation of electrically driven transformations in 2050, it essential that several technologies with a large potential impact on the industry have been demonstrated at TRL7 in 2030. At least 2-3 mayor routes to convert $CO_2$ into chemicals or fuels should be demonstrated on industrial scale at TRL9 in 2035.

Progress in the electrochemistry field can be achieved by a merger of electrochemistry with conventional chemical ideas, such as organocatalysis and flow electrochemistry, as well as new procedures for controlling the selectivity of electrochemical transformations such as the “cation-pool” method, the redox-tag approach, and bio-electrochemistry.

For the innovation objectives identified:

- **Development of electrochemical processes to create high added value chemicals at low temperatures:** Current TRL is 3-4 (depending on the processes), aiming at
    - New reactor design (electrochemical conversion to more complex molecules requires innovative approaches for electrode design and materials, nanostructures, electrolyte (system)s, catalysts and membrane materials is required to develop specific solutions for the targeted molecules.
    - Key parameters to optimise include the current density, Faradaic efficiency, electrode lifetime, overpotential, while minimising the use of scarce materials (e.g., Iridium) or toxic materials (mercury, lead).
    - Significantly reduced cost of electrodes (developing cheaper, durable catalysts, new electrocatalytic approaches and new processes based on electrochemical conversion).
    - Novel reactor concepts enabling effective scale-up, reducing the cost of the integrated system up to the desired product, including down-stream processing.
- **High temperature electrochemical reactors for syngas and chemicals:** Current TRL is 3-4 (depending on the process), aiming at the same programmatic development needs as for the high added value chemicals, but with even more emphasis on cost reduction and scale up. Additionally, the lifetime of cells operating under industrially relevant compositions (syngas with a wide range of H/C ratios) is still a relatively unexplored area and is more challenging at the higher temperatures.
    - High temperature electrolysis (solid oxide electrolysis) is a topic of intense research as a method to produce hydrogen but is especially interesting for industrial applications as a potential technology to efficiently produce syngas or even pure CO using $CO_2$ as feedstock.
- **Radical new electrochemical processes to produce non-chemical energy-intensive materials:**
    - Electrochemical formation of cement is currently at TRL 3 (MIT, 2019).
    - Not yet programmed.

### 6.5.1.4 Investment needs

**Table 9: Investment needs in € million – work in progress and subject to change**[27]

| Technology: | Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total: |
|---|---|---|---|---|---|---|---|---|
| **Development of electrochemical processes to create high added value chemicals at low temperatures** | 2020-2030 | | 9x €4 (2025) | 5x €20 | | | | |
| | 2030-2040 | | 9x €4 | 5x €20 | 3x €40 | | | |
| | 2040-2050 | | 9 x €4 | 5x €20 | 3x €40 | | | |
| **High temperature electrochemical reactors for syngas and chemicals** | 2020-2030 | | 2x €20[28] (2025) | 2x €20 | | | | |
| | 2030-2040 | | 2x €20 | 2x €20 | 1x €100 | | | |
| | 2040-2050 | | 2x €20 | 2x €20 | 1x €100 | | | |
| **Radical new electrochemical processes to produce non-chemical energy-intensive materials** | 2020-2030 | *<< to be done >>* | *<< to be done >>* | *<< to be done >>* | | | | |
| | 2030-2040 | *<< to be done >>* | *<< to be done >>* | *<< to be done >>* | | | | |
| | 2040-2050 | *<< to be done >>* | *<< to be done >>* | *<< to be done >>* | | | | |
| | **TOTAL** | €0 | €228 | **€420** | €440 | €0 | €0 | €1088 |
| | *% public funding* | | | | | | | |
| | ***Public funding*** | | | | | | | |

### 6.5.1.5 Success factors

- Needs to use cheap abundantly available renewable electricity;
- Needs to use "green $CO_2$";
- Electro organic synthesis or electrochemical conversion of hydrocarbons needs to transform from a niche technology to a common synthetic method. Therefore, electrosynthesis also has to find its place in teaching and student training. The sustainability of this particular approach will make the use of this method inevitable at an academic and a technical level.
- Requires the trade-off between stabilising the changes in supply of electricity by operating the new electrochemical processes flexibly (implications: storage facilities for the produced products - partially solid, liquid, gas – required) versus flexibility in the downstream processing versus other options to stabilise the electricity network (allowing these processes to continuously operated at maximum capacity) to be sorted out;
- Scarce materials are used in the electrodes, and thus an infrastructure to recycle these is required.

[27] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.
[28] Cost-wise this is the "big jump"; one pilot would be dedicated to design a reactor to be tested in the field, and the other to test this reactor in the field.

### 6.5.2 Electrically-driven separation

#### 6.5.2.1 Innovation objectives

Significant amounts of thermal energy are used for separation. Electrically-driven separation could perform separation using considerably lower amounts of energy for the same functionality, in the form of "no greenhouse gas emitting electricity". To this end, a toolbox of technologies with several innovation objectives needs to be developed. These objectives are:

- **Reducing cost of innovative electrically-driven separation processes:** Most separation processes use heat to achieve the separation of components, e.g. distillation, absorption/desorption, adsorption/desorption processes. Removal of components at low concentration, either for product recovery or for water purification is energy intensive. Alternative, electricity-based processes, such as electrodialysis and membrane capacitive de-ionisation, are not used for bulk processes because they are not cost competitive. However, increased demand for separation of low concentration components and electrification of the industry, opens the potential for high-volume applications. However, substantial reduction of capital cost is necessary.
- **Implement innovative pressure-driven separation processes:** Pressure driven processes such as ultrafiltration, nanofiltration, reverse osmosis or pervaporation can replace conventional processes (e.g. distillation). The separation process is driven by pressure, which is generated by electrically driven pumps or compressors. This type of technology will not only replace existing separation processes. Where substantial amounts of streams containing (valuable) materials are now used as fuel, increasing use of heat pumps and electrical heating will lead to increasing demand for recovery of the usable components from these often-gaseous streams. An example is the recovery of hydrogen or other components using gas separation with high selective membranes.

This toolbox can then be applied to several applications:

Applications:

- **Near Zero-water-discharge-plant:** Minimising the use of fresh water in processes and by closing the water loop completely is a key aspect in reducing the environmental footprint of the future process industry. This requires technologies to remove low concentration chemical species from aqueous streams. A key factor is that these streams typically contain multiple impurities (such as salts and organic residues) making separation more complex.
- **Reduce cost of down-stream separation for bio-based processes**: Inherently resources from non-thermal bio-based processes (e.g. fermentation) are highly diluted. Downstream processing is one of the main bottlenecks in developing cost effective biobased processes. Objective is to reduce the cost of downstream processing by 20% compared to conventional processes.
- **Replace thermal distillation**: Thermal distillation is mostly applied in the chemical industry and in refineries and uses a hot and a cold stream (either delivered by heat integration or by boilers/cooling water) to separate substances on the basis of differences in volatility. These processes are typically energy intensive, and significant amounts of energy can be saved with electrically driven separation technologies.
- **Valorisation of gaseous combustible waste streams** can are present in installations in the chemical industry and refineries, but also in for example steel plants ($CO/H_2$). Better separation allows more high-value application of the valuable components.

#### 6.5.2.2 Impacts

**GHG emissions:**

**Near Zero-water-discharge-plant:** estimated at 25% of the waste water's electricity consumption; as electricity is assumed to have an emission factor 0 in 2050 --> no GHG emissions saving. The large buffering ponds offer the potential for flexibility in use (demand side management.

**Reduce cost of down-stream separation for bio-based processes**: Enabling technology for bio-based chemical production.

**Replace thermal distillation**: Chemicals: 50% of the chemical industry's energy use is in separation (distillation + absorbtion; based on the Netherlands), of which an estimated 20% is consumed in separations in aqueous systems. An estimated 20% of this 50% (mainly the shorter hydrocarbons, and aqueous systems ) could be replaced by new separation technologies, which boils down to 10% of the chemical industry's energy use – for which a 100% emission reduction would be the consequence.

**Valorisation of gaseous combustible waste streams:** Ultimately, provided that the applications for the separated and valorised waste gases do not end up being emitted (or replace products that would otherwise lead to the same fossil emissions), the full GHG emissions contained in these waste streams are saved (the separation for valorisation just requires renewable electricity), which is estimated to be 2% of the chemical industry's GHG emissions - taking into account that the options to burn these gases will be reduced in future due to the application of other heating technologies.

| Sector | Current Emissions in EU, MtCO2e | Emissions targeted by the IP, % | Reduction within targeted emissions, % | Emission reduction impact, MtCO2e |
|---|---|---|---|---|
| Cement | 105 | | | |
| Steel | 190 | | | |
| Chemicals | 128 | 12% | | |
| Ceramics | 17 | | | |
| Non-ferrous metals | 18 | | | |
| Minerals | 19 | | | |
| Water | 27 | 0% | | |
| **Total SPIRE-CCNI** | | | | |

<u>**Waste:**</u>

- **Near Zero-water-discharge-plant:** Full prevention of waste water discharge; quantity off valorised components in waste water: Not known.
- **Other applications:** no impact.

<u>**Competitiveness:**</u>

**Near Zero-water-discharge-plant:** Developing these technologies help to make meeting the goal of zero discharge of waste water achievable at lower cost.

**Reduce cost of down-stream separation for bio-based processes**: Enabler

**Replace thermal distillation**: Energy cost-wise high amounts of heat are replaced by a small amount of electricity, significantly reducing OPEX cost. However, the investment in membranes is (still) very high, which often leads to a non-competitive business case. To illustrate:

**Valorisation of gaseous combustible waste streams:** Depends on the composition of the waste gas, for example there may well be cases where separating off hydrogen is competitive.

#### 6.5.2.3 Programming

For this innovation programme, a toolbox of technologies, including membrane technologies, needs to be developed, which can be applied to a whole variety of applications (refer to the innovation objectives). Currently, these technologies are at various TRL levels. For many technologies, it would take around 10 years to bring them to TRL 7 and then 5 years to bring them to TRL 9 (relatively short as these are modular systems). To do so, a whole-system approach (design, engineering, production and testing) needs to be followed. For each technology brought to TRL 9, a non-technological component needs to be added to ensure:

- Awareness (knowledge dissemination, educational system);
- Modelling tools.
- Build up trust by validating the technologies in smaller scale (lower risk) markets first

#### 6.5.2.4 Investment needs

**Table 10: Investment needs in € million – work in progress and subject to change[29]**

| Technology: | Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total: |
|---|---|---|---|---|---|---|---|---|
| **Develop toolbox of technologies** | 2020-2030 | | 18x €5 | 6x €35 | | | | |
| | 2030-2040 | | 18x €5 | 6x €35 | 3x €50 | 3x €2 | | |
| | 2040-2050 | | 18x €5 | 6x €35 | 3x €50 | 3x €2 | | |
| | ***Total*** | | | | | | | |
| | **TOTAL** | €0 | €270 | €630 | €300 | €12 | €0 | €1212 |
| | *% public funding* | | | | | | | |
| | ***Public funding*** | | | | | | | |

#### 6.5.2.5 Success factors

- Developing the market (currently, the market volume is limited, leading to high costs), supply chain, proving the technology and gaining credibility;
- Financing of SME's (there are many in the supply chain; having funds available for investments);
- Reducing non-technological barriers;
- Cross sectoral cooperation (learn from other sectors – like the food industry – that already apply membranes).



[29] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## 6.6 Integration of hydrogen production, use and storage

This innovation area focuses on the implementation of low-emission hydrogen into the process industries. Currently, in some industries, like the chemical industry and refineries, hydrogen produced from natural gas is already used, with strong upward potential for its use as a GHG emission reduction measure. Other sectors, like the steel sector, could become consumers of significant amounts of hydrogen in the future in case the carbon for the reduction step would be replaced by hydrogen. The GHG emissions of the current production will need to be reduced to zero.

This innovation area therefore covers three innovation programmes:

- **Alternative routes for the production of hydrogen:** Currently, the two most explored routes towards production of hydrogen without GHG emissions are blue hydrogen (production of hydrogen from natural gas in combination with CCS) and green hydrogen (production of hydrogen on the basis of electrolysis: 2 $H_2O$ – 2 $H_2$ + $O_2$). We assume that development of these two production routes will be included in the Fuel Cells and Hydrogen Joint Undertaking and do thus not focus on these production routes. Several alternative hydrogen production routes are developed too, however, and their further development needs are covered in Innovation Programme, “Alternative routes for the production of hydrogen.”
- **The integration of no emission hydrogen in the process industries:** The use of hydrogen as abatement measure in the process industries requires innovations and their deployment. Integration of hydrogen production or use of hydrogen instead of fossil-based fuels in industrial sectors is the key task in Innovation Programme, “Introducing no emission hydrogen in the industrial processes.”
- **Storage of hydrogen:** Because some of the new production routes of hydrogen use renewable electricity, which production depends on the variable availability of wind/sun, there will be a benefit of being able to store hydrogen. This will be described in Innovation Programme, “Storage of hydrogen.”

### 6.6.1 Alternative routes for the production of hydrogen

#### 6.6.1.1 Innovation objectives

The technologies below are, next to blue and green hydrogen, currently foreseen for the future production of hydrogen with lower/without GHG emissions:

- **Pyrolysis of methane:** Process technology to produce hydrogen from natural gas, but also biogas, landfill gas or synthetic methane. This technology splits natural gas directly into its components, hydrogen and carbon. Methane pyrolysis follows the reaction $CH_4$ --> C + 2 $H_2$; by taking methane as the starting point, the energy input in the reaction is relatively limited; the formed solid carbon can potentially be used in steel or aluminum production, and in tires, concrete admixtures, as soil improver/Terra preta and as filling material. The aim is to demonstrate the first commercial unit before 2030. This methane pyrolysis process requires comparatively little energy. If this energy comes from no greenhouse gas emitting sources, hydrogen can be produced on an industrial scale without CO2 emissions.
- **Photoelectrocatalysis (PEC):** This process directly converts solar energy into the energy required for the decomposition of water (similar reaction as for the production of green hydrogen). PEC cells operate at ambient pressure and temperature and at lower potentials than electrolysis which makes PEC more energy efficient. Furthermore, PEC decouples H2 production from external electric input which make H2 production independent from natural gas and electricity costs.
- **Thermochemical/thermoelectrochemical water splitting:** This hydrogen production process consists of oxidising a metal oxide or an oxidable fluid in the presence of water,

producing hydrogen. The metal oxide is regenerated at high temperature by stripping oxygen.

- **Electrochemical $H_2S$ splitting:** Using similar technologies (electrolysis and photoreactors) as for the production of green hydrogen from water, hydrogen can also be produced from $H_2S$, which is a by-product of refineries and natural gas processes[30], also with bi-functional hydrogen generators that can process $H_2S$ and water as a feedstock.
- **Bio-based production of Hydrogen (gasification of biomass):** Biomass gasification produces hydrogen using steam. With suitable gas cleaning technology and separating off $CO_2$ with new reactor concepts, hydrogen can be produced from biomass, a low hydrogen containing renewable raw material. This concept fits nicely with H4C, as biomass gasification can be an integrated part of a wider bio-economy-valorising all the valuable components from the biomass first and then gasifying the remaining parts.

*<< In the absence of much information received about plasmalysis, this technology is not included in this version >>*

#### 6.6.1.2 Impacts

***GHG emissions***

These technologies lead to the following GHG emission reduction:

- Pyrolysis of methane: Maximum 0,26 t $CO_2$/t $H_2$ (FutureCamp, 2019) from the production of methane[31];
- Photoelectrocatalysis: Up to 95%;
- Thermochemical/Thermoelectrochemical water splitting: Up to 95% if the energy requirements are supplied by solar energy;
- Electrochemical $H_2S$ splitting;
- Gasification of biomass: Could be negative, when the $CO_2$ produced is captured and stored or used.

This reduction could be applied to the full current production of hydrogen (now 8 million tonnes/year in Europe (FCH JU, 2018)), with an average GHG emission emissions of 80 million tonnes/y $CO_2$.[32] In the future, much more hydrogen will likely be produced for use in the process industry (see the next innovation programme, and for the production of fuels/chemicals/polymers with CCU), which is anticipated to strongly increase the significance of alternative hydrogen production routes, including blue and green hydrogen.

***Waste***

The current production of hydrogen doesn't lead to the production of any solid waste. Of the alternative production methodologies mentioned above, the following solid by-products are obtained:

- Pyrolysis of methane: Solid carbon is formed as by-product; in case this could not all be sold for applications, then the excess solid carbon would need to be stored – which doesn't seem to be in line with SPIRE-CCNI's no-landfilling ambition for 2050 – therefore it is key that all the by-product can be sold to other markets in which it doesn't lead to landfilling/GHG emissions.
- Photoelectrocatalysis: No waste produced.
- Thermochemical/Thermoelectrochemical water splitting: No waste is produced.

[30] $H_2S$ splitting can thus be considered as the electrification of the desulfurisation process in these industries.
[31] Total GHG effect will depend on the use and end-of-life treatment of the by-product solid C.
[32] Assuming that all $H_2$ is produced by SMR (in reality: 95%) and a ratio of 9,7 t $CO_2$ /t $H_2$ produced with that technology.

- Electrochemical H2S splitting: The sulfur produced is used the production of several compounds as sulfuric and sulphydric acids, carbon sulfides and others. It is also used in the production of the black gunpowder and of insecticides, pharmaceutical products and disinfectants.
- Gasification of biomass: No solid waste is generated, when the produced char is used or energy/steam production on the process.

***Competitiveness***

<to be added in the next version>

### 6.6.1.3 Programming

- **Pyrolysis of methane:** Expectation to have a proof of concept, a pilot plant and the demonstration plant (first commercial unit) all before 2030; the process challenges for the upscaling from lab to pilot scale are:
  - Need for basic R&D and new reactor design;
  - Heating concept needed to overcome the low radial heat transfer from the wall into the reactor core;
  - Manage inhomogeneous flow and pulsations;
  - High-temperature materials required.
- **Photoelectrocatalysis** is still at an early R&D phase. Development would aim at achieving:
  - Increased stability and lifetime of the electrodes;
  - Discovery/development of suitable photoelectrodes and photocatalyst;
  - Optimisation of reactor design;
  - Solar to hydrogen conversion efficiency > 20%;
  - Reducing the CAPEX cost by reducing PEC module costs < 100 €/m2 (since the technology is CAPEX intensive, representing around 80-90% of total costs);
  - The non-technological investment needs concern regulatory, standardization, awareness and educational issues.
- **Thermochemical/thermoelectrochemical water splitting**
  - **Research needs (+ timing):**
  - For thermochemical/hybrid cycles small MW range prototype demonstrations are needed. Additionally, the technology needs to go to TRL 7 from TRL 5-6;
  - Investigate the use for high-temperature industrial waste heat;
  - Developing efficient and robust reactor designs compatible with high temperatures and heat cycling;
  - Increase efficiency and durability.
- **Electrochemical $H_2S$ splitting**
  - **Research needs (+ timing):**
  - H2S electrolysis currently is at TRL4, needs to go to TRL 6 by 2030;
  - Then a demo for refinery and natural gas process units is needed in 2040-2050;
  - Development non-Pt group electrocatalyst currently at TRL 2 need to go to TRL 5. Platin group electro-catalyst initially can be used and later replaced by non-Pt electro-catalyst to lower OPEX.
- **Bio-based production of Hydrogen (gasification of biomass):**
  - **Research needs (+timing):**
  - Bio-based production of hydrogen by syngas production and separation of $H_2$ and $CO_2$ by different reactor concepts currently at TRL 5-6 needs to go to TRL 9; The important topic is cleaning of syngas and separation of the hydrogen formed is the important topic.

#### 6.6.1.4 Investment needs

**Table 11: Investment needs in € million – work in progress and subject to change**[33]

| Technology: | Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total: |
|---|---|---|---|---|---|---|---|---|
| **Pyrolysis of methane** | 2020-2030 | | Number not yet known | Number not yet known | | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Photoelectrocatalysis** | 2020-2030 | 6x €2.5 | 3x €10 | 2x €12 | 2x €15 | 2x €1 | | |
| | 2030-2040 | | 3x €10 | 2x €12 | 2x €15 | 2x €1 | | |
| | 2040-2050 | | | 2x €12 | 2x €15 | 1x €1 | | |
| | ***Total*** | | | | | | | |
| **Thermochemical/ Thermoelectrochemical water splitting** | 2020-2030 | | 3x €12 | 2x €20 | | | | |
| | 2030-2040 | | | | 2x €20 | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Electrochemical H2S splitting** | 2020-2030 | 3x €2 | 2x €8 | 1x €10 | | 2x €1 | | |
| | 2030-2040 | | 2x €8 | 1x €10 | | 2x €1 | | |
| | 2040-2050 | | | | 2x €12 | 2x €1 | | |
| | ***Total*** | | | | | | | |
| **Gasification of biomass** | 2020-2030 | | | | 2x €35 | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| | **TOTAL** | €21 | €128 | €132 | €284 | €11 | €0 | €576 |
| | *% public funding* | | | | | | | |
| | ***Public funding*** | | | | | | | |

[33] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

#### 6.6.1.5 Success factors

- Pyrolysis of methane: << *to be added* >>
- Photoelectrocatalysis:
  - Solar to hydrogen efficiency > 20%;
  - PEC module costs < 100 €/m2 (since the technology is CAPEX intensive, representing around 80-90% of total costs).
- Thermochemical/Thermoelectrochemical water splitting (DOE, Technical plan-production, 2012):
  - Solar to Hydrogen (STH), energy Conversion Ratio of 26%;
  - Cycle time of 1 min/cycle.
- Electrochemical $H_2S$ splitting:
  - The energy price (electricity) should be below €0,2/kWh. Then $H_2S$ electrolysis will become economically feasible.
- Gasification of biomass: Realisation of the process chain from biomass supply, gasification process, syngas cleaning and integration of produced hydrogen in industrial sectors.

### 6.6.2 Introducing no emission hydrogen in the industrial processes

#### 6.6.2.1 Innovation objectives/programming

This programme focuses in the need of retrofitting or complete changing the different processes of the industry were the low carbon hydrogen could be used. This innovation programme covers a couple of innovation objectives:

- **Improving combustion in furnaces can be improved in two manners:**
  - **By using hydrogen rather than fossil fuels:** When hydrogen would be produced without GHG emissions, replacing fossil fuels (such as natural gas or coal) by hydrogen eliminates the GHG emissions completely. Currently used furnaces are often not equipped to use hydrogen, as:
    - Different types of burners would be needed;
    - The higher flame temperature and different radiation of hydrogen-combustion causes a need to adjust (retrofit) the combustion system and the conductive zone of the furnace;
    - Hydrogen-based combustion leads to higher volumetric gas flows;
    - The higher amount of water generated creates the need to adjust the off-gas system (increase water separation capacity and for potential corrosion – when a mixture with a sulfur-containing fossil fuel is used);
    - Different steel types may be needed (not all currently used steel may be apt for hydrogen).

    This technology is currently at TRL 5.

  - **By using oxygen rather than air:** When the hydrogen used is green hydrogen, or when a green hydrogen plant is close by for other applications, significant amounts of oxygen are formed as by-product. Using this oxygen in combustion reactions reduces the energy use of the combustion – as there is no longer a need to heat all the nitrogen in the air. There is scope to use this oxygen by-product in combustion reactions, as it can be expected that there will be a surplus of oxygen-by-product, for example only 15% of the oxygen-by-product that is formed in the hydrogen production for DRI in the steel industry would be needed in the steel industry – with the other 85% becoming available for other applications. Using oxygen rather than air leads to:
    - A higher temperature;
    - Other off-gas temperatures;
    - Smaller air separation units/compressors.

This technology is currently not at the higher TRL.

- **Using hydrogen in the steel industry:** There are three manners in which hydrogen can be introduced as reducing agent:
    - Integration of decentralized hydrogen production in a **classical integrated** BF/BOF or DR/EAF steel plant and use of the hydrogen combined with other process gases in the different steps of the process chain;
    - Development of **new process concepts** for steelmaking based on hydrogen and alternative raw materials;
    - Use the **decentralized hydrogen** production for internal and external electrical grid stabilizing and integration of the oxygen from the electrolysis in the steel plants energy system.
- Using hydrogen in the **non-ferrous** metals industry: Hydrogen can be used as a reducing agent for some **pyro smelting processes** (e.g. copper)[34], aluminium, in ferro-alloys, and in the recovery of metals from smelting slag or leaching residues (Wyns, 2019).
- **Integrating hydrogen as a feedstock in the chemical and refining sector:** Apart from replacing the currently used hydrogen, new process routes to produce platform chemicals can also be developed. These include (the other CCU-routes to produce fuels, chemicals and polymers are described in other innovation programmes):
    - Ammonia, which can for example be produced by reacting no emission hydrogen with nitrogen; the produced ammonia can be used for:
        - Its current applications, mainly as fertiliser
        - New applications of ammonia in furnaces and in gas turbines
    - Methanol, which can for example be produced by reacting no emission hydrogen with $CO_2$;

  In case the production of no emission hydrogen would be dependent on renewable electricity:
    - The availability of the no emission hydrogen might fluctuate; this is treated in the next objective
    - Oxygen by-product might be formed: which can be used for combustion reactions (see above) or as oxidising agent in processes like water treatment, chemical industry, nitric acid, or to improve the efficiency and the business case of some technologies like gasification of biomass/waste.
- **Dealing with variations of the hydrogen supply:** In case the production of no emission hydrogen would be dependent on renewable electricity, the hydrogen will not always be produced; this can either be tackled by storing hydrogen (see next innovation programme) or by making processes robust for variations in the hydrogen supply, by:
    - Allowing variations in the capacity (the process industry now typically operates continuous processes at constant (maximum) capacity);
    - Using fossil natural gas/bio gas as a backup: This requires installations which can switch smoothly. Only in the case of bio gas will the operation remain at zero GHG emissions.

  The process industry is currently not at all used to operating under such flexible conditions.

#### 6.6.2.2 Impacts

- Improving combustion in furnaces – using hydrogen:
    - No impact on waste
    - GHG emission – impact of replacing the furnaces fuel by zero emission hydrogen is 100%; when fully applied:
        - For chemical industry: naphtha crackers: perhaps 20-25%;

[34] Smelters already requiring a lot of O2 might have better business case for use of H2 via electrolysis, which has O2 as a by-product.

        - For lime industry: ±33% (as process emissions are 2/3 and not impacted);
        - For steel industry: maximum 10%, heating and annealing furnaces, but not the primary steelmaking processes;
        - For cement industry: ±33% (as process emissions are 2/3 and not impacted);
        - For ceramics industry: Up to 100%, depending on how the furnaces are fired;
        - For refineries industry: ±30-50%, depending of the refinery scheme.
        - Non-ferrous metals: H2 as fuel can replace fossil fuels for heating purposes. Potential emission reduction 7.5-10% of the sectors scope 1 emissions, with cross-sectoral innovations needed in burner design;
    - Competitiveness: At current energy cost and hydrogen cost and carbon cost, this is by far not competitive. Needs much cheaper and abundant no emission hydrogen.
- Improving combustion in furnaces – using oxygen:
    - No impact on waste;
    - GHG emissions: using oxygen rather than air (thus removing the inert gases from the combustion air) increases the useful heat available to the process from 59% to 79% of the higher heating value with an expected fuel savings of 26%. The actual increase in the available heat is system-dependent, but high fuel savings are possible using oxygen (Air Products and Chemicals, Inc, 2010) (approximately similar for all sectors);
    - Competitiveness: The improved energy efficiency (less fuel (for example hydrogen) needed) has the potential to improve the competitiveness, although today it is an expensive technology.
- Using hydrogen in the steel/non-ferrous metals industry - increasing the use of hydrogen in the classical integrated iron&steel production route:
    - Reduction of waste: No impact[35]; Less pollution to the environment from the cokes oven plant;
    - Potential of GHG emission reduction: Up to 30%;
- Using hydrogen in the steel/non-ferrous metals – industry – new process concepts:
    - Reduction of waste: No impact; No pollution to the environment from the cokes oven plant anymore.
    - Potential of emission reduction: More than 80% (assuming some natural gas would still be needed). *Note that this implies that 100% emission reduction would be feasible in combination with using bio-gas for the remaining fuels.*
- Using **decentralized hydrogen** in the steel industry:
    - *<< to be added >>*
- Using hydrogen in the **non-ferrous metals** industry:
    - Potential to reduce emission: 5% voor Al en Cu production;
- Using hydrogen in the steel/non-ferrous metals – industry – general:
    - Competitiveness: Need cheap green hydrogen (technology development, electricity, policies, or other technologies delivering cheap no-emission hydrogen).
- Using hydrogen in the chemical and refining industry:
    - No impact on waste
    - GHG emissions, when zero emission hydrogen is used:

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[35] The amount of waste from the cokes plant is reduced, but as this waste is used within the process anyhow, this is more an efficiency effect.

        - Ammonia: -100% emissions, applied to 22% of the chemical industry's GHG emissions[36];
        - Methanol: -100% of emission, applied to <10% of the chemical industry's GHG emissions[37] (CCU process, not just replacing emissions from the plant, but also producing "emission free" methanol)
        - Rest of chemical industry: 100% of the emissions from hydrogenation, which are 10% (all apart from ammonia and methanol).
        - Refinery: 20% of emissions of total refinery are from hydrogen production, this can be completely eliminated.
    - Competitiveness: Need cheap green hydrogen (technology development, electricity, policies, or other technologies delivering cheap no-emission hydrogen).
- Dealing with variations of the hydrogen supply: This is more an enabling effect (enabling the other measures to be taken) --> no separate impact.

### 6.6.2.3 Investment needs

*<< Table is not yet complete >>*

**Table 12: Investment needs in € million – work in progress and subject to change[38]**

| Technology[39]: | Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total: |
|---|---|---|---|---|---|---|---|---|
| **Improving combustion in furnaces – using hydrogen** | 2020-2030 | | | 5x €5-10 | | | | |
| | 2030-2040 | | | 5x €5-10<br>5x €30 | 5x €30 | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Improving combustion in furnaces – using oxygen** | 2020-2030 | | | | | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Using hydrogen in the steel/non-ferrous metals industry - increasing the use of hydrogen in the classical integrated iron and steel** | 2020-2030 | | | | 3x €50[40] | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |

[36] Using (Ecofys, 2009), ignoring the nitric acid and adipic acid related emissions.
[37] Using (Ecofys, 2009), ignoring the nitric acid and adipic acid related emissions.
[38] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.
[39] Cost include the cost for electrolysers.
[40] To allow development for two different variants of blast furnaces.

| Technology[39]: | Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total: |
|---|---|---|---|---|---|---|---|---|
| **production route** | | | | | | | | |
| **Using hydrogen in the steel industry - new process concepts** | 2020-2030 | | 3x €30 (before 2025) | | 3x €50 | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Using decentralized hydrogen in the steel industry** | 2020-2030 | | | | | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Using hydrogen in the non-ferrous metals industry** | 2020-2030 | | 3 x €4 | | 1 x €200 | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Using hydrogen in the chemical and refining industry** **Dealing with variations of the hydrogen supply** | 2020-2030 | | | 2 x €35 | 1x €40[41] | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| | **TOTAL** | €0 | €102 | €295 | €690 | €0 | €0 | €1,087 |
| | *% public funding* | | | | | | | |
| | ***Public funding*** | | | | | | | |

### 6.6.2.4 Success factors

- Integration of decentralised hydrogen production in steel and non ferrous metals plants and combination with the plants energy system;
- At both European and national legislation level, the recognition of the role green hydrogen can play, and legislation introducing a clear methodology such as mass balancing to account for its use in chemical processes is needed to support its introduction.

[41] Provided that cheap electricity/green hydrogen, or policy support (for example the Innovation Fund), are available in time, as the scale of these currently not competitive innovation investments is too big to already do them in their absence). Perhaps TRL 7-8.

### 6.6.3 Storage of hydrogen

#### 6.6.3.1 Innovation objectives

The use of hydrogen produced from renewable electricity implies that the hydrogen might not always be available in constant quantities. Hydrogen could, in periods of availability of excess renewable electricity, be converted to natural gas, or other fuels. These are, apart from ammonia, treated in the CCU innovation areas. Alternatively, the hydrogen consuming production processes could reduce their production speed (see above). Finally, the direct storage of hydrogen, which is a task in this innovation programme, enables constant availability of hydrogen for the process industry. Therefore, the innovations required for storage of hydrogen and for the use of ammonia as hydrogen carrier are described here.

This programme will focus on:

- **Storage of hydrogen:** Developing a system for storage of excess renewable energy is a key topic, and direct storage of hydrogen is one of the options. The success of this technology is the key for the transformation of the fossil-based energy system to renewables. Only this large-scale storage can solve the storage problem of fluctuating renewable energy and continuous hydrogen supply for the process industry. Hydrogen can be directly stored in underground natural gas storage areas, as well as in depleted oil and gas fields or salt caverns. For the recovery process, for example from natural gas storage, separation technologies for natural gas and hydrogen are necessary.
- **Ammonia as hydrogen carrier:**
  - Development and scale-up of innovative ammonia production, storage, needs to go to TRL 9 in 2030
  - Decomposition and direct use of ammonia needs to go to TRL 8 2027.

#### 6.6.3.2 Impacts

- **Storage of hydrogen:** Hydrogen produced by several technologies on a continuous or a fluctuating operation can be compressed and stored underground in different existing installations. Impacts:
  - Impact on GHG emissions: << *to be filled in* >>
  - No impact on waste.
  - Impact on competitiveness:
    - Hydrogen storage increases cost – thus to maintain competitiveness the cost increase needs to be as low as possible;
    - This large storage options allows the shifting of excess renewable energy from e.g. summer season to winter season. Thus, energy shifting effects also the competitiveness of renewable energy, as it prevents shutting down installations during periods with low energy demands and high production.
- **Ammonia as hydrogen carrier:** << *Not yet filled in* >>

#### 6.6.3.3 Programming

Storage and recovery technology has to be demonstrated in an industrial scale with real renewable energy generation.

- For storage of hydrogen: Technology has to be developed from TRL 5-6 to 7-9.
- For ammonia as hydrogen carrier: << *To be filled in* >>

### 6.6.3.4 Investment needs

**Table 13: Investment needs in € million – work in progress and subject to change**[42]

| Technology: | Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|---|
| **Hydrogen storage** | 2020-2030 | | | 3x €35 | | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Ammonia as hydrogen carrier** | 2020-2030 | | | | | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| | **TOTAL** | €0 | €0 | €105 | €0 | €0 | €0 | **€105** |
| | *% public funding* | | | | | | | |
| | ***Public funding*** | | | | | | | |

### 6.6.3.5 Success factors

*<< to be filled in >>*

[42] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## 6.7 Capture and purification of $CO_2$

### 6.7.1 Flexible $CO_2$ capture and purification technologies

The main objective is the development of flexible carbon capture and purification technologies for separation of $CO_2$ from industrial flue and process gases. The aim is to facilitate development of flexible, modular, energy- and cost-efficient capture and purification technologies that enable storage, for deep emission cuts, and valorisation of $CO_2$, by exploiting $CO_2$ as carbon source in e.g. fuels and chemicals. Technology development is needed to enable deep emission cuts from industry towards 2030 and further towards 2050. The overall objective is to develop technologies that lower the threshold for implementing $CO_2$ capture in European industries, thereby enabling CCUS to be a part of the emission reduction measures. $CO_2$ capture and purification technology development is necessary with the ultimate goal of providing the industries with a portfolio of technologies that, either alone or together, can cater to the needs of any industry (varying in size, flue gas composition) and downstream $CO_2$ valorisation. Development of CCUS technologies for implementation in EU industries will ensure that the deep emission cuts needed by 2030 and 2050 can be reached while maintaining global competitiveness.

#### 6.7.1.1 Innovation objectives

Innovation objectives for ***Flexible and modular capture technologies:***

- to reduce $CO_2$ capture CAPEX by more than 20% by 2030 and by 50% in 2050 compared to current technologies
- to reduce $CO_2$ capture energy consumption by more than 15% in 2030 and 25% in 2050 compared to current technologies
- utilisation of more sustainable materials, (absorbents, adsorbents, membranes) by eliminating the waste by 2050 (e.g. by using materials that can be recycled)
- demonstration of flexibility towards different gas compositions ($CO_2$ concentration and impurities)
- demonstration of modularity (also units of 10kt should be available at lower cost)

Innovation objectives for ***Flexible and modular $CO_2$ purification technologies for higher concentrated sources:***

- Develop purification technologies that can produce a $CO_2$ stream of the quality needed for different $CO_2$ valorisation pathways
- Develop purification technologies that can be integrated downstream of $CO_2$ capture and upstream of $CO_2$ valorisation

#### 6.7.1.2 Impacts

***GHG emissions***

This is not relevant here, because it is already discussed under the carbon utilisation programmes.

***Waste***

Carbon capture enables recycling the carbon in other applications. However, because $CO_2$ is a gaseous effluent it does not contribute towards the target of zero landfilling and water discharge.

About 3.2kg of anime reclaimer waste is created per tCO2 captured when using MEA (Flø, 2017). This waste can be used as NOx reduction agent or can be combusted. Alternatively, they can also be treated (aerobic digestion). Adsorbents can be reused and membranes can be burned or reused.

***Competitiveness***

This innovation programme aims to decrease the costs of carbon capture. As such, it will contribute to increased competitiveness of carbon capture technologies as well as the CCU applications presented in the other innovation programmes. The CAPEX accounts for around one third of the capture costs, solvents around 4% and energy costs cover the rest (Flø, 2017). Therefore, the energy reductions in the technologies are key to achieve competitiveness.

#### 6.7.1.3 Programming

***Flexible and modular capture technologies***

There is currently a considerable amount of research and development ongoing within the field of $CO_2$ capture. However, R&D is still needed towards flexible, modular, energy- and cost-efficient capture technologies. The four main categories of capture technologies are; absorption, adsorption, membrane, and cryogenic (or low-temperature) separation.

Technology development needs include:

- Highly integrated concepts at a system level, taking into account upstream of the $CO_2$ capture point and downstream for $CO_2$ valorisation
- Development of modular capture technologies (such an approach could contribute to reducing the risk and cost of $CO_2$ capture for the industry as a modular approach will enable a stepwise increase in captured volume.) such standardisation would enable the development of a lean supply chain and cost savings. CAPEX is around one third of the capture costs, so CAPEX reduction can have a significant impact.
- Process intensification allowing for significant energy and cost reduction, and reduced footprint of technologies
- Completely new approaches to $CO_2$-capture
- Highly efficient, long-lasting membranes coupling high permeability and selectivity,
- Solid adsorbents like zeolites, activated carbons, mixed metal oxides and others (e.g. Cao)capturing more than 100 mg $CO_2$/kg while being resilient to impurities in the gas streams
- Develop fully integrated hybrid concepts, i.e. combining two $CO_2$ capture technologies, that when combined show a significant added benefit regarding energy- and cost reduction

In addition, circularity of the materials used for CO2 capture will be considered.

This Innovation programme aims to develop small, modular processes for capturing $CO_2$ at a competitive cost and an appropriate quality for various $CO_2$ valorisation routes.

***Flexible and modular $CO_2$ purification technologies for higher concentrated sources***

As an expansion to the need for $CO_2$ capture technology development, $CO_2$ purification technology development is also needed. Here, primarily two applications are foreseen; Further purification of already captured $CO_2$ and for the purpose of conforming to specifications of upstream $CO_2$ valorisation pathways, for flue gases with an already high $CO_2$ concentration. The second application includes flue gases coming from oxygen enriched or full oxy-combustion processes.

Oxyfuel technology has the potential to be less energy- and cost-intensive compared to post combustion technologies. The use of oxygen in the combustion reaction can result in a more concentrated flue gas (see 6.6.1 Alternative routes for the production of hydrogen). Nevertheless, the CO2-concentration in the exit gas is lower than amine technology and will be in the range of 90% CO2. On top, the oxyfuel 'fluegas' has ruled out most of the Nitrogen, yet it contains the regular minor components that flue-gases of industrial processes like cement do have in their flue-gas, such as SOx, NOx, HF, HCl etc. As such it is like the raw gas input of an amine-capture unit, but then with less N2. Therefore, the technology development required is to find a cost- and eco-effective way to eliminate these minor components on top of the 'normal' requirements of a CPU.

As several downstream CCU-processes require a higher concentration and purity level, effective CPU units are required to be developed. The optimal value chain for the various CCU-categories should be explored.

***Direct air capture***

The above technologies focus on point sources of $CO_2$ emissions. It is also possible to capture $CO_2$ directly from the atmosphere. Since the concentration in the atmosphere is several orders of magnitude lower than in point sources, the energy consumption and therefore costs are higher. Direct air capture (similar to capture of $CO_2$ from bio-origin) offers the potential to build CCU value chains for short-lived applications with zero net GHG emissions, which is especially relevant on the longer term (climate neutrality). Direct air capture could also be an option in cases where no $CO_2$ emission point sources or alternative carbon feedstocks are available. With $CO_2$ captured from the atmosphere high volumes of climate neutral materials, for example “no GHG emission” fuels (e.g., for use in aviation, where a high energy density is required) can be produced.

Direct air capture technologies are similar to end-of-pipe capture and concentration technologies, but more development is required to make them more cost-effective. The energy footprint and CAPEX is a bigger issue to be addressed in innovation efforts. Investing in the further development of direct air capture enables continued large scale application of CCU for short-lived applications in a carbon neutral future. The programme will focus first on the point source technologies, and then build on these technologies to move to direct air capture.

#### 6.7.1.4 Investment needs

The Innovation programme ***for flexible and modular capture and purification*** is foreseen with:

- **Until 2030**: R&D of 9 times €3 million, demo-projects of 4 times €15 million, 2 extra demo-projects for possible short-term value chains (2 times €25 million), R&D for DAC of 2 times €3 million.
- **2030-2040**: Development and testing of flexibility of capture and purification technologies and deployment in 5 different applications (different purity/contaminants) (€25 million each) to develop a more universal technology; 2 pilots for DAC of €15 million and demonstrating first generation of DAC at €50 million.
- **2040-2050**: demonstrating second generation of DAC at €50 million. deployment of 100 modular units of 50-100 $ktCO_2$/yr with investment of 1,000 M€.

**Table 14: Investment needs in € million – work in progress and subject to change[43]**

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| **2020-2030** | 9x €3<br>2x €3 | 4x €15 | 2x €25 | | | | €136 |
| **2030-2040** | | 2x €15 | 5x €25 | 5x €25 | €5 | | €130 |
| **2040-2050** | | | | 1x €50 | | €1,000 | €1,000 |
| **Total** | €33 | €90 | €175 | €175 | €5 | €1,000 | €1,478 |
| ***% public funding*** | | | | | | | |
| ***Public funding*** | | | | | | | |

[43] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

#### 6.7.1.5 Success factors

- Demand for $CO_2$ as feedstock (linked to the other innovation programmes) need for customers, and the willingness of companies to invest.
- Policies are key to provide incentives for $CO_2$ capture and utilisation. The gap should be filled between what this innovation programme can achieve in terms of cost reductions and the cost needed to have a business case.
- Increasing the $CO_2$ concentration of industrial flue and processes gases through process intensification. The increased concentration enables lower capture and purification costs both in CAPEX and OPEX. At the same time this will reduce the total volume of flue gas, which is an added benefit. Similarly, lower levels of impurities would enable lower-costs. In innovation programme 6.10.4 Breakthrough process design for improved energy and resource efficiency, technologies are developed to achieve this.

## 6.8 $CO_2$ to minerals

### 6.8.1 $CO_2$ valorisation during concrete production

Fresh concrete for pre-cast elements can be cured under a $CO_2$-environment. During this curing process, $CO_2$ will enter into the fresh concrete and react with the Ca(OH) present in the poured concrete to create $CaCO_3$ and as such sequester $CO_2$ into the concrete matrix. Besides sequestering $CO_2$ in the product, the strength development is also enhanced, so in order to reach the same performance of concrete the kg of cement per m3 of concrete can be reduced, reducing further the overall $CO_2$-footprint of the $m^3$ concrete at given strength.

This only applies to pre-cast concrete because a curing chamber is needed because it takes time before the $CO_2$ is fully reacted. Also, moisture and temperature levels should be managed. Up to 20% of all cement is in pre-cast and this share is increasing.

This technology is developed for special type of cement (wollastonite) already by companies reaching TRL9. It is, however not used much because the special cement is needed, and it is difficult to convert the kilns. Applying this same technological concept to regular cement cements requires further deployment as it is currently around TRL5.

Making this technology commercially available for regular cements will facilitate faster deployment and more general application of the technology to cure fresh pre-cast concrete with $CO_2$. Especially investigations and test with respect to porosity, optimal recipes for fresh concrete and equipment to make low-capital-intensive curing chambers available is mandatory.

Note that this technology is different from concrete curing, a technology that adds several kg of liquid $CO_2$ into ready mix concrete when it is being poured. This acts as an accelerator/agitator for hardening process. It does not bind to all the calcium hydroxide in the mix and only relatively small volumes of $CO_2$ are used.

#### 6.8.1.1 Innovation objectives

- Development of regular pre-cast $CO_2$-curing from TRL 5 to TRL 9
- Development of special reinforced precast $CO_2$-curing from TRL 2 to TRL 9

#### 6.8.1.2 Impacts

***GHG emissions***

Wollastonite technology reduces $CO_2$ by up to 60%. As it only applies to pre-cast applications, which are about 20%, the total potential reduction is equal to 12% of cement emissions. With total emissions of 105 $MtCO_2$ in the cement sector, the reduction potential of this technology is 12.6 $MtCO_2$.

***Waste***

Carbon capture enables recycling the carbon in other applications. However, because $CO_2$ is a gaseous effluent it does not contribute towards the target of zero landfilling and water discharge.

***Competitiveness***

It is expected that this technology would be competitive with regular pre-cast concrete at TRL9. There are additional costs compared to regular pre-cast concrete production, but the additional strength enables using less material.

#### 6.8.1.3 Programming

Development towards 2030

- Maturing the TRL-level of this application by demonstration plants using standard Portland cement and delivering CO2-cured precast products to the market
- Developing the recognition of the pre-cast concrete customers that low-carbon pre-cast products are being developed and should be marketed as such.

Development towards 2050

- Rapid deployment of CO2-curing in precast concrete market by combination of commercial benefits, stimulating regulations (low carbon concrete products) and know-how support to precast producers.
- Widening the application-range of CO2-curing by R&D into stainless steel reinforcement or carbon fibres reinforcement for pre-cast reinforced elements that with normal iron reinforcement bars are not suitable for CO2-curing.

#### 6.8.1.4 Investment needs

- Until 2030: R&D of 6 times € 3 million, demo-projects of 4 times 10 € million, and for deployment 10 projects each supported by 2 million €);
- 2040-2050: deployment of .. with investment of

**Table 15: Investment needs in € million – work in progress and subject to change[44]**

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| **2020-2030** | | 6x €3 | 4x €10 | 4x €12 | €5 | €100 | €211 |
| **2030-2040** | | 4x €3 | 4x €10 | 4x €12 | €5 | €500 | €605 |
| **2040-2050** | | | | | | €400 | €400 |
| **Total** | €0 | €30 | €80 | €96 | €10 | €1000 | €1216 |
| ***% public funding*** | | | | | | | |
| ***Public funding*** | | | | | | | |

#### 6.8.1.5 Success factors

- Developing the recognition of the pre-cast concrete customers that low-carbon pre-cast products are being developed and should be marketed as such
- Rapid deployment of CO2-curing in precast concrete market by combination of commercial benefits, stimulating regulations (low carbon concrete products) and know-how support to precast producers

### 6.8.2 Circular construction materials by re-carbonation

The fine fraction of recycled concrete has an enormous potential to sequester $CO_2$. Concrete re-carbonates over time. In buildings, over the course of about 50 years the outer 2 cm of the concrete reacts with $CO_2$ from the air. However, when recycling the concrete at the end of its life, there is opportunity to sequester more $CO_2$.

The actual main objective when recycling concrete is to reuse the coarse fraction as a secondary aggregate in fresh concrete or as a stabilisation product for road construction. The fine parts are usually not valorised. However when the fines are further treated (milling/separation) to get the cement-paste as a fine particle back, the Ca(OH) in this material will react very easily with $CO_2$ to form $CaCO_3$ particles in a structure that makes it a useful building material. Such re-carbonated fines do have cementitious properties at minimum of the level of fly-ash that is used for decades in Portland composite cements.

An advantage of this form of CCU compared to others is that flue gases do not need to be purified in most cases; the flue gases can directly react with the recycled concrete fines

Technology development as well as regulatory measures are needed to exploit the full potential of this CCU-approach. The handling and injection of the recycled concrete fines (RCF) inside the flue-gas and the recollection of the carbonated RCF out of the flue-gas are the main

[44] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

developments. Focus should be on capture efficiency, handling of fines, long term availability of 'scrubber' area where the $CO_2$ is captured etc.

CaO and/or MgO rich materials that are by-products or recycled materials (such as steel-slag and recycled concrete fines) are generally much more reactive than natural materials, thus requiring less energy to execute the re-carbonation. As for example end-of-life concrete is to a large extend being landfilled and recycled concrete is used 'only' for road stabilisation the enormous hidden potential of the reactive CaOH inside end-of-life concrete is not used. The carbonation of a well separated part of these circular materials, will result into a large $CO_2$ sequestration and into valuable (building) materials.

#### 6.8.2.1 Innovation objectives

- Produce composite cement containing >20% in mass of re-carbonated RCF in 2030 and 30-40% in 2050
- Development of re-carbonation of RCF from TRL 3 to TRL 9 in 2030
- Development of high substitution composite cements from TRL 2 to TRL 9
- Development of integrated CO2-capture and valorisation from TRL 3 to TRL 9

#### 6.8.2.2 Impacts

***GHG emissions***

The re-carbonation can sequester 0.1t$CO_2$ per tonne waste concrete according to a recent study (Pasquier, Kemache, Mocellin, Blais, & Mercier, 2018). With about 50 million tonnes waste concrete generated in Europe annually, this implies a potential impact of 5MtCO2.

Additionally, new cement is displaced, resulting in additional $CO_2$ emission reductions.

***Waste***

This innovation programme addresses concrete waste in Europe. This is about 50 million tonnes per year (Pasquier, Kemache, Mocellin, Blais, & Mercier, 2018).

Carbon capture enables recycling the carbon in other applications. However, because $CO_2$ is a gaseous effluent it does not contribute towards the target of zero landfilling and water discharge.

***Competitiveness***

The re-carbonated cementitious material is as good as fly ash. The current value of fly ash ranges from 1/3 to 2/3 of that of cement. Landfill ban on this material should create the incentives as well as the carbon price (if this will incentivise CCU in the future).

#### 6.8.2.3 Programming

Development towards 2030

- Maturing the TRL-level of this application by demonstration plants where the energy-efficiency of the separation of the recycled concrete fines will be optimised, as well as the logistical concept for reclaiming materials and making $CO_2$ available for the reaction are further developed
- Maturing the technology of direct capture and valorisation by RCF in existing flue-gas systems, by taking a slipstream of the flue-gas and treat that with RCF
- Designing integrated systems that can account for the complete flue-gas quantity
- Focus on the quality of the carbonates created and the marketability of such products in the building material supply chain

Development towards 2050

- Refine further the technology to exploit the maximal potential of end-of-life concrete in terms of $CO_2$ sequestration
- Further development of the technology in order to increase its applicability

#### 6.8.2.4 Investment needs

- **Until 2030**: R&D of 6 times € 3 million, demo-projects of 4 times € 10 million, and for deployment 20 projects each requiring € 5 million
- **After 2030**: Deployment

**Table 16: Investment needs in € million – work in progress and subject to change**[45]

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| **2020-2030** | | 6x €3 | 4x €10 | | | €100 | 158mln |
| **2030-2040** | | | | | | €500 | 500mln |
| **2040-2050** | | | | | | €400 | 400mln |
| **Total** | €0 | €18 | €40 | €0 | €0 | €1000 | €1058 |
| ***% public funding*** | | | | | | | |
| ***Public funding*** | | | | | | | |

#### 6.8.2.5 Success factors

- Realise regulatory measures to avoid concrete being landfilled and avoid that recycling is done only for course material recovery, but that the fine fraction must be used as well
- Adapt specifications and norms allowing for RCF to be part of composite cements
- Stimulate markets to use cement/concrete with a certain share of recarbonated RCF
- Rapid deployment of business of RCF re-carbonation, using optimal logistical concepts for each application

### 6.8.3 Natural materials mineralisation (e.g., olivine carbonating $CO_2$)

Natural minerals like olivine, serpentine and basalt have the potential to sequester $CO_2$, due to their content of CaO and MgO in the rocks. In nature, this process of mineral carbonisation is developing very slowly (decades up to centuries) as the access of $CO_2$ to the carbonatable fractions is limited. By mining those minerals, increasing surface area and by lifting temperature and pressure, the process of mineralisation can be accelerated in such a way that full potential is exploited within a reaction time of 1 hour.

Technology development is needed especially in the domain of energy-efficiency as minerals require crushing/milling and increased temperature and pressure in order to accelerate the mineralisation process. The separation of final products and the determination of maximum market value of the final products needs further investigation.

Finally, the logistics related to making minerals available near to the $CO_2$-source or opposite needs further investigations and demonstrations. Currently, research is being conducted on how much cement can be displaced by such materials and what the full value chain impact and business model could look like.

#### 6.8.3.1 Innovation objectives

The objective is to

- Develop natural minerals carbonation from TRL 3 to TRL 9 by 2035
- Assess the mitigation potential of the full value chain and decide whether to continue

#### 6.8.3.2 Impacts

***GHG emissions***

[45] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

In this innovation programme the application of the technology where there is no demand for the carbonated minerals is excluded. Mining materials with the sole purpose to carbonate them and then discarding them (landfilling or infilling) is therefore not included in this estimation.

It is not certain where carbonated natural minerals can displace other materials, but a reasonable proxy is the market size of fly ashes in cement production. 34 million tonnes of fly ash were produced in Europe in 2013 (European Climate Foundation, 2018). If this volume can be fully substituted (as coal phases out in the future), and assuming the need of 2.5 tonnes rock per tonne CO2, 34 Mt of carbonated mineral is equivalent to 10 MtCO2.

***Waste***

Carbon capture enables recycling the carbon in other applications. However, because $CO_2$ is a gaseous effluent it does not contribute towards the target of zero landfilling and water discharge.

***Competitiveness***

Carbonation of minerals is only competitive if there is market demand for the carbonated materials. Whether there is a business case for the carbonated natural mineral compared to alternatives relies on the specific application and local circumstances.

### 6.8.3.3 Programming

Development towards 2030

- Maturing the TRL-level of this technology where the energy balance is key, as an optimum should be found between amount of $CO_2$ per tonne of mineral and the energy needed to achieve it.
- Developing autoclaves that can work most effectively for the purpose of this mineralisation process
- Focus on the highest level of application of the generated products
- Optimise the logistics between mining operations, the $CO_2$-source and the market for the final products generated

Development towards 2050

- Implementation of the most ecological and economical applications
- Further development of the technology in order to increase its applicability



### 6.8.3.4 Investment needs

**Table 17: Investment needs in € million – work in progress and subject to change[46]**

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| **2020-2030** | | 3x €3 | 2x €8 | | | | €25 |
| **2030-2040** | | | 2x €8 | | | | €25 |
| **2040-2050** | | | | 4x €12 | €4 | €400 | €452 |
| **Total** | €0 | €9 | €32 | €48 | €4 | €400 | €493 |
| ***% public funding*** | | | | | | | |
| ***Public funding*** | | | | | | | |

### 6.8.3.5 Success factors

- Policies on waste and GHG are necessary to provide incentives for users to switch from their current materials to carbonated minerals.

[46] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## 6.9 $CO_2$ valorisation to chemicals, polymers, and fuels

Several target molecules can be used as chemical or as energy carrier, and the related technology developments needed will be the same while the non-technical issues and related impact will be different. The related technology development for chemical and energy carriers will be under the same innovation programme, and the distinction regarding application will be made at the level of the objective in each innovation programme. The below overview shows what routes are available.

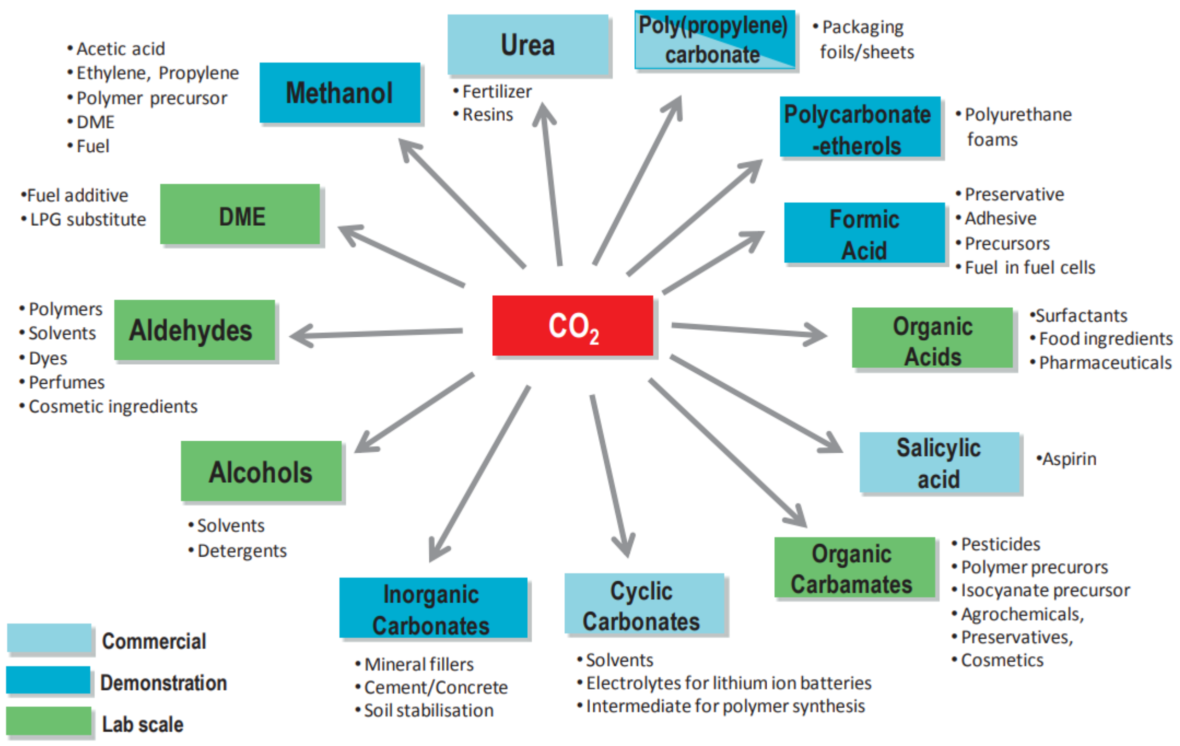


**Figure 14: Target molecules of chemical $CO_2$ utilisation routes and status of development (DECHEMA, 2017)**

According to the European Commission's Long Term Strategy CCU is expected to play a major role in 2050. See below the volume of CO2 captured to produce synthetic fuels (European Commission, 2018). Additionally, CCU can be used to produce carbon-based chemicals.

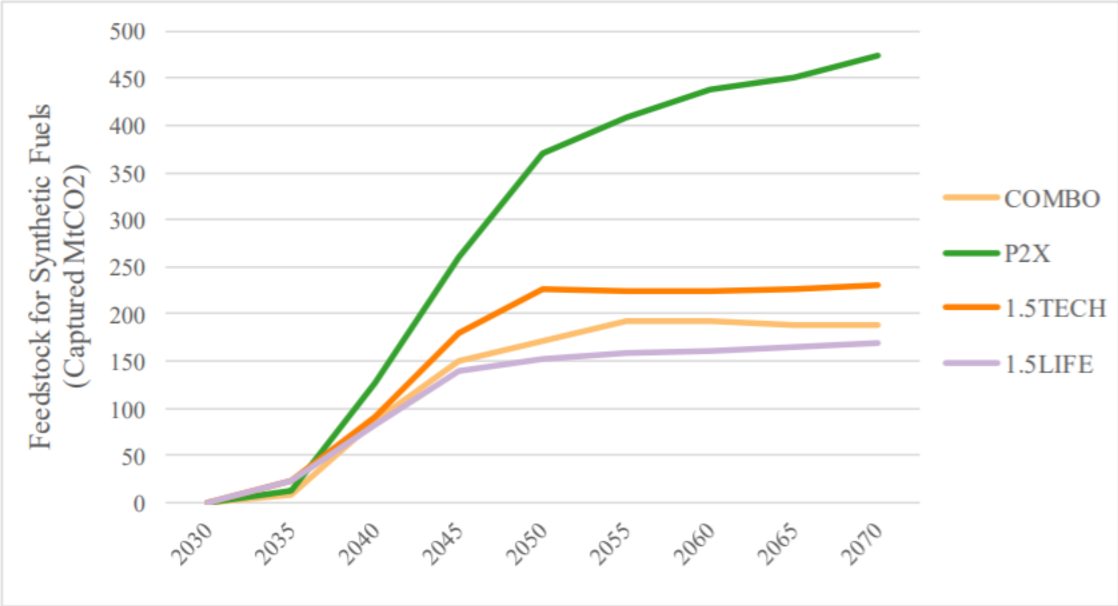


**Figure 15: Expected CCU for fuels according to EC scenarios (European Commission, 2018)**

In this innovation area, four innovation programmes are distinguished. The first three focus on use of $CO_2$. Two of these three aim for using $CO_2$ to build chemical building blocks (photocatalytic and other catalytic technologies) and the third on direct use of $CO_2$ in polymers. The fourth focuses on CO from industrial processes.

## 6.9.1 Direct utilisation of sunlight (Artificial photosynthesis)

This programme focuses on the development of disruptive technologies that allow the production of chemicals and fuels based on $CO_2$, water and energy from sunlight.

In order to increase efficiency, selectivity, stability and reduce the cost of technologies for the chemical $CO_2$ valorisation through direct utilisation of sunlight, advanced integrated photo(electro)catalytic systems have to be developed for the conversion of $CO_2$ to $C_1$ molecules and the conversion of $CO_2$ to $C_{n+1}$ molecules. In this way energy carriers as well as intermediates for high added value chemicals will be selectively produced in sustainable photocatalytic processes.

Such advanced photo(electro)catalytic systems require the development of:

- Highly efficient and long-term stable materials for photo(electro)catalytic cells components.
- Fluid dynamics and integrated photo(electro)catalysis system modelling (see innovation programme 6.15.1 Towards digitally supported design of environmentally benign high-performance materials) gaining knowledge of internal cell process (photogenerated charge carriers generation, separation and transfer, heat and mass transfer, kinetics, charge separation and transfer, degradation, bubble formation, growth and evacuation) for optimising and accelerating prototypes designs and technology scale-up
- Development of low energy intensive concentration systems for $CO_2$ derived liquid materials in order to reach required product concentration levels
- Advanced materials and high performance catalysts that will reduce energy requirements for $CO_2$ reduction and water splitting in an economic and sustainable way.

### 6.9.1.1 Innovation objectives

The objectives are to:

- Produce chemicals through $CO_2$ to $C_1$ and $CO_2$ to $C_{n+1}$ conversions with low carbon footprint independently of the availability of renewable electricity

- Production of fuels $C_{n+1}$ molecules with low carbon footprint for chemicals and energy carrier application independently of the availability of renewable electricity
- Reduce the energy consumption to produce chemicals and fuels

#### 6.9.1.2 Impacts

***GHG emissions***

The H2020 project SUN-to-LIQUID, which synthesised kerosene from sunlight, reports a potential of over 90% compared to conventional fossil-derived jet fuel (SUNtoLIQUID, 2019). With European aviation emissions in the area of 163Mt$CO_2$, this would mean a reduction potential of 147Mt$CO_2$ (EEA, EASA & EUROCONTROL, 2019). There are limits to the availability of space in Europe that could limit the potential. Other applications of this technology could target other emissions and have other potential (e.g. other fuels or chemicals).

***Waste***

The chemical valorisation of $CO_2$ can effectively contribute to the development of a more circular economy. However, because $CO_2$ is a gaseous effluent it does not directly contribute towards the target of zero landfilling and water discharge.

***Competitiveness***

The costs of direct production of fuels or chemicals from sunlight are CAPEX driven because it does not require additional energy input. However, because the technologies are still immature, it is not possible to estimate the CAPEX at full-scale deployment.

To illustrate what CAPEX level would be necessary to be competitive, an illustrative calculation is made for a system of 1m$^2$. Assuming an efficiency of 20% and a capacity factor of 30%, this 1 m$^2$ system will generate 526kWh of fuel each year (i.e.,1,892GJ). With a current kerosene price of €0.75/liter and gross calorific value of 37.1 MJ/liter, that amounts to total revenues of €38 per year for this 1 m$^2$ system. At a 10% discount rate and 25-year lifetime the capital recovery factor is 11%, and the annuitised CAPEX of the same €38 per year is achieved at a CAPEX of €347.

#### 6.9.1.3 Programming

Before 2030 - Design of new and efficient Photoelectrocatalysts (PEcats) for the development of competitive systems to convert sunlight, $H_2O$ and $CO_2$ into valuable materials, intensification of solar to chemical energy process.

Photo(electro)catalytic technologies should be developed:

- To TRL 4-5 for photocatalytic
- To TRL 5-7 before 2030
- TRL 7-9 before 2050

#### 6.9.1.4 Investment needs

**Table 18: Investment needs in € million – work in progress and subject to change**[47]

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| **2020-2030** | 8x €2.5 | 8x €8 | 2x €20 | | | | €124 |
| **2030-2040** | | 6x €8 | 4x €20 | 2x €160 | | | €448 |
| **2040-2050** | | | 4x €20 | 2x €160 | | €850 | €1,250 |
| **Total** | €20 | €112 | €200 | €640 | €0 | €850 | €1,822 |
| ***% public funding*** | | | | | | | |

[47] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ***Public funding*** | | | | | | | |

### 6.9.1.5 Success factors

- Complementary topics to address the intermittency of the energy source (see also innovation programme 6.1.1 Integration of renewables)

## 6.9.2 Catalytic conversion of $CO_2$ (excluding photocatalytic and direct use in polymers)

### 6.9.2.1 Innovation objectives

The objectives are to:

- Develop framework to compare different routes and applications
- Produce chemicals through $CO_2$ to $C_1$ molecules and $CO_2$ to $C_{n+1}$ molecules with lower environmental footprint compared to current production route – including net CO2 emission reduction evaluated with appropriate system boundaries and methodology .
- Production of $C_{n+1}$ molecules with low carbon footprint for chemical and energy carrier applications.
- Contribution to renewable electricity storage in chemical energy carriers via the conversion of $CO_2$ through Power-to-X technologies

### 6.9.2.2 Impacts

***GHG emissions***

Several studies have assessed the potential for the utilisation of $CO_2$ as carbon feedstock for the production of fuels and chemicals.

- DECHEMA considered several scenarios for the deployment of CO2 to methanol, olefins, BTX and fuels with an impact of 64 million tonnes CO2 avoided /y for the related materials in 2050 in an ambitious scenario (DECHEMA, 2017).
- In the EC Long term strategy, the potential for CCU for production of synthetic fuel is estimated at 150 MtCO2 and 225 MtCO2 in 2050 in the 1.5LIFE and 1.5TECH scenarios, respectively (European Commission, 2018).

As other options exist for alternative carbon feedstock, such as biomass and waste, the evaluation of the impact at European level is difficult.

***Waste***

The chemical valorisation of $CO_2$ can effectively contribute to the development of a more circular economy.. However, because $CO_2$ is a gaseous effluent it does not contribute towards the target of zero landfilling and water discharge.

***Competitiveness***

Like with the estimation for the GHG impact, the competitiveness of CCU options is difficult to estimate. As an indication we show here the existing assessment from Dechema for Methanol form $CO_2$ based on existing technologies. For other target molecules the results will differ. A generic rule is that the more of the original CO2 molecule remains, the more attractive the route is.

*Methanol*

Dechema analyzed the costs of producing methanol in a catalytic conversion of CO2 (DECHEMA, 2017). The below table from the report shows the production costs at different electricity prices and hours of operation. Methanol produced from fossil feedstock costs around 400 €/t. This means that renewable electricity should be available at prices below 22 €/MWh (i.e. 6 €/GJ) at 7000 h/year or 16 €/MWh (i.e. 4.5€/GJ) at 5000 h/year. Note that this analysis does not take technological development into account, and therefore with technological improvements costs can be reduced and therefore the technology might be competitive in 2050 at higher electricity prices.

**Table 15: Costs of production for renewable methanol assuming different hours of operation**[67]

| Renewable electricity price [€/MWh] | | 10 | 30 | 50 |
|---|---|---|---|---|
| **Methanol production costs [€/t]** | at 7000 h/year | 290 | 469 | 670 |
| | at 5000 h/year | 335 | 536 | 737 |
| | at 3000 h/year | 447 | 625 | 826 |

When using the methanol as a fuel, Dechema found that it would be competitive to bioethanol production costs at 1.5 to 2.5 €ct/MJ, but is a factor 2 above conventional gasoline production (DECHEMA, 2017). Note that Dechema used different underlying assumptions than used in this roadmap and therefore this analysis is inconsistent with the analyses conducted for other innovation programmes.

### 6.9.2.3 Programming

Technologies currently scaling to TRL 5-6 (e.g. electrochemical based reduction, Fischer-Tropsch starting from $CO_2$ rich streams and renewable hydrogen, (thermal) (super) dry reforming, catalytic chemical looping) should evolve to TRL 7-8 by 2030. This can be in terms of reactor designs, unit operations such as integration with separation processes, flexible energy grid use, process design and operability, process scale up, improvement of previously identified catalytic systems with respect to stability (lifetime) and selectivity, etc.

New technologies or technologies with still major hurdles with respect to catalyst development (yield, selectivity, stability), reactor designs, unit operations such as integration with separation processes, flexible energy grid use, process design and operability at TRL below 5 but with a potential of surpassing the current TRL 5 -9 technologies, should increase at least 1 TRL scale by 2030. This includes hurdles such as the use of electrocatalysis for specific target molecules at higher yields, plasma-based processes towards syngas or CO, plasma catalytic processes to C2-Cn+1 components, ionic liquid based technologies, or bio or electrocatalysis.

Integrated processes such as sorption enhanced processes or integrated separation. Different TRL's can be expected depending on the TRL level of the individual technological components and the challenges with respect to their integration. A clear benefit of their integration should be obtained with respect to environmental, sustainability or techno-economic aspects. A framework for selection will be developed for this purpose.

Especially for lower-TRL technologies the innovation programme will need to use insights to decide which technologies are most promising. This portfolio approach will continue towards 2040 to continuously identify and develop opportunities for more (efficient) technologies. Since there are many important aspects to the prioritisation of technologies, a multi-criteria approach is recommended for the selection of projects, such as the below from (Jarvis & Samsatli, 2018).

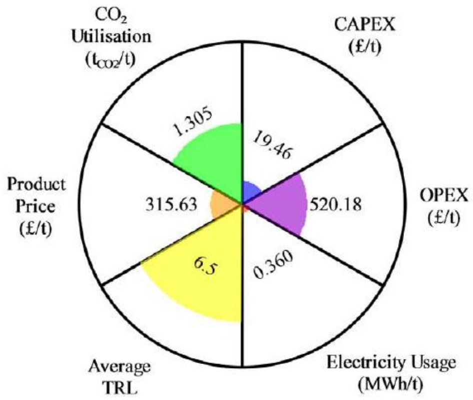


**Figure 16: Example of a framework for CCU technology (in this case hydrogenation to methanol) assessment (Jarvis & Samsatli, 2018)**

Non technological barriers include the need for dedicated guidelines enabling a common understanding of how to evaluate the environmental impact of $CO_2$ valorisation technologies for various applications.

Technology developments are needed to:

- Improve the economics of the conversion of $CO_2$ to $C_1$ molecules
- Move conversion of $CO_2$ to C $_{n+1}$ in one step reactions to TRL 3 before 2025, TRL 5 by 2035, TRL 7 before 2035, TRL 9 by 2040.
- To create integrated and intensified processes, linking different technologies to create process intensification as they are expected to enhance impact. TRL 4 before 2030, TRL 5 by 2040, TRL 7 by 2050
- Where the catalyst is still the issue lower TRL activities are required with TRL 6 as objective for by 2050

Technology priorities include:

- The utilisation of less purified streams of $CO_2$ with the purpose of minimising the cost of the purification phase or with the purpose of using poison resistant catalysts
- Robust $CO_2$ conversion process with high productivity
- Development of highly active and selective catalysts with sufficient lifetime, for more efficient processes (see also innovation programme 6.10.1 Advanced catalysis providing raw material flexibility and lower energy inputs through alternative chemical pathways)
- Valorisation processes at lower temperature and/or pressure
- Integrated processes where separation, (waste/recovery) heat and/or sorption are integrated with the conversion process with the intention to intensify its performance
- Integrated processes where mixtures of CO and $CO_2$ can be used without or with limited separation
- Process design linking unit operations including electric grid integration
- Catalytic – including Electrocatalytic processes for the transformation of CO2 into CO

#### 6.9.2.4 Investment needs

A broad portfolio of technology options should be explored to cover the various production routes from $CO_2$ to various $C_1$ and $C_{n+1}$ molecules.

The first wave of technologies are the ones that are already in the pipeline. Additionally, the second wave should be created in the 2020-2030 period (low-TRL). Then in 2030-2040 new low-TRL technologies are developed to improve the technologies. This will be necessary to find breakthrough technologies. Technologies then should show that they have more potential then the ones in higher TRL.

**Table 19: Investment needs in € million – work in progress and subject to change[48]**

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| **2020-2030** | 5x €3 | 8x €10 | 3x €20 | | €3 | | |
| **2030-2040** | 5x €3 | 13x €10 | 10x €20 | 6x €25-150 | €5 | | |
| **2040-2050** | | | 3x €20 | 3x €25-150 | | €1,000 | |
| **Total** | €30 | €210 | €320 | €787.5[49] | €8 | €1,000 | €1,793 |
| ***% public funding*** | | | | | | | |
| ***Public funding*** | | | | | | | |

#### 6.9.2.5 Success factors

- Multi-criteria analysis in a standardised manner to evaluate the impact of technologies for various applications
- Access to low-carbon hydrogen or electricity at competitive prices
- Cost-effective $CO_2$ capture and purification technologies (see innovation programme 6.7.1 Flexible $CO_2$ capture and purification technologies)
- Policy framework for applications (chemical, transport, energy storage)

### 6.9.3 $CO_2$ (and $CO_2$/CO) to polymers

$CO_2$ can be used as an alternative carbon resource to produce polymers through two major chemical routes: either by using directly $CO_2$ as polymer building block or indirectly by using intermediates which obtained by chemical transformation of $CO_2$. Several $CO_2$-to-polymer technologies have been already successfully demonstrated at lab and pilot scale, and a first demo plant built in Europe.

The innovation programme will focus on:

- the direct production of polymers from CO2 : by 2030 at least one large-scale commercial plant based on technologies developed and the development of polymers from $CO_2$ for new applications (differential and competitive, and by 2050 Scale up to industrial scale of new applications.
- the production of polymers from CO/$CO_2$ to be moved from TRL 4 to higher TRLs.

#### 6.9.3.1 Innovation objectives

- Incorporate up to 15-30% in weight of $CO_2$ in polymers by 2030 (the remainder being bio-based, recycled, $CO_2$-based monomers, or fossil)
- produce polymer materials with a reduced carbon footprint of at least 15% for the first generation of technology (to avoid that technologies are developed that are more energy intensive)
- Incorporate up to 20-40% in weight of $CO_2$ in polymers by 2050 (the remainder being bio-based, recycled, or $CO_2$-based monomers)
- produce new polymeric structures for high performance materials polymers from CO2 with new properties. At least one large-scale commercial plant by 2025, 3 demonstration plants , and one multi-purpose plant.

#### 6.9.3.2 Impacts

***GHG emissions***



[48] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.
[49] Based on the average of the ranges

Total polymer market is very big, however only Polyols and PPC can currently be addressed. These product groups collectively accounted for 8-10 million tonne of product in 2015 globally, and are expected to grow to 17 Mt in 2030 (CO2 Sciences, 2016). Experts estimate that in 2030 1-10% of these materials can be produced with 25% CO2. For this estimation we assume 5% in 2030. Towards 2050 this could go to 50% of molecules, and 40% of CO2 included. This means that CO2 used amounts to (17*5%*25%=) 0.2MtCO2 globally in 2030 and (17*50%*40%=) 3.4 MtCO2 in 2050.

It is not unimaginable that some of the polyols and PPCs have functionalities that enable displacement of other polymers, and a x2 multiplier is used to account for that. The resulting total technical potential in 2050 is estimated at 7MtCO2 globally. Europe is assumed to have a market share of 20%, so the EU potential is 1.4MtCO2 in 2050.

Note that this is very uncertain due to the many assumptions about technology development and development of product demand. Also, additional impact is possible due to the displacement of polyols and PPC from fossil production routes.

***Waste***

The utilisation $CO_2$ as an alternative carbon feedstock for the production of polymers can effectively contribute to the development of a more circular economy. However, because $CO_2$ is a gaseous effluent it does not contribute towards the target of zero landfilling and water discharge.

***Competitiveness***

There are significant market entry barriers for new polymers. New products are difficult to sell to customers, as they need to test it for their functionality and their application. To offset these transaction costs, either better properties are needed or lower costs. This means that the polymer should be produced at lower cost.

For some polymers with CO2 the energy consumption is lower. Therefore, this technology could be competitive already on the short term. The competitiveness would be strengthened when the ETS would incentivise CCU.

#### 6.9.3.3 Programming

Development towards 2030:

- More efficient catalyst: Catalyst optimisation for increased $CO_2$ conversion, Catalyst removal/reuse (6.10.1 Advanced catalysis providing raw material flexibility and lower energy inputs through alternative chemical pathways)
- Use of les purified $CO_2$/unpurified $CO_2$
- Improved downstream purification (more effective and less costly) (6.10.3 Innovative processes to maximise use of secondary raw materials)
- Development of product applications for the new polymers

Development towards 2050:

- Development of new applications for the new polymers
- Polymers from direct of valorisation of CO2 :
- polycarbonate-etherols (Polyol):
  - Low Mw: from TRL 6 to TRL9
  - High Mw: from TRL 4 to TRL 9
- poly(propylene)carbonate TRL 6 to TRL 9

#### 6.9.3.4 Investment needs

For CO2 by 2030: least one large-scale commercial plant, at least 3 demo plants (incl. + multipurpose plants), and at least 3 pilot projects for CO2-based polymers with new properties.

For CO2/CO by 2030: at least one pilot and one demo for CO/CO2

2M€ for each project at TRL 1-3; 5M€ for each project at TRL 4-6; 15-25 M€ for demo plant (5kt/y) TRL 7-8, and 100 M€ for and world scale plant, (50 kt/y) TRL 9.

**Table 20: Investment needs in € million – work in progress and subject to change[50]**

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| **2020-2030** | 6x €2 | 4x €5 | 4x €20 | 2x €100 | | 2x €100 | €512 |
| **2030-2040** | | 2x €5 | 5x €20 | 3x €100 | | 3x €100 | €710 |
| **2040-2050** | | | 6x €20 | 3x €100 | | 3x €100 | €720 |
| **Total** | €12 | €30 | €300 | €800 | €0 | €800 | €1,942 |
| ***% public funding*** | | | | | | | |
| ***Public funding*** | | | | | | | |

### 6.9.3.5 Success factors

- Bio-based or CO2-based ways to produce non-fossil co-monomers

## 6.9.4 CO captured from industrial waste gases to chemicals and fuels

Currently CO streams from blast furnaces in the steel sector are typically used to generate electricity. However, as the energetic value of CO is higher than of CO2, it can also be used as a feedstock to produce chemicals and fuels. This innovation programme aims to develop and demonstrate technologies to do this. Such technologies could potentially also be used in biogas installations, as these also produce CO streams.

As with regular CCU options based on CO2, also with CO there are many possible routes. For example, ArcellorMittal in Ghent and Dow Chemicals in Terneuzen already have started a pilot to produce ethanol from the CO stream (TRL. 7-8), but there is also a pilot for CO to synthetic naphtha. The diagram below illustrates the concept in Ghent/Terneuzen. It illustrates the many processes that need to work together to create the fuel of chemical from CO. Specific challenges are related to the high diluent amount in the steel gas, as well as specific impurities that need to be removed to allow valorisation.

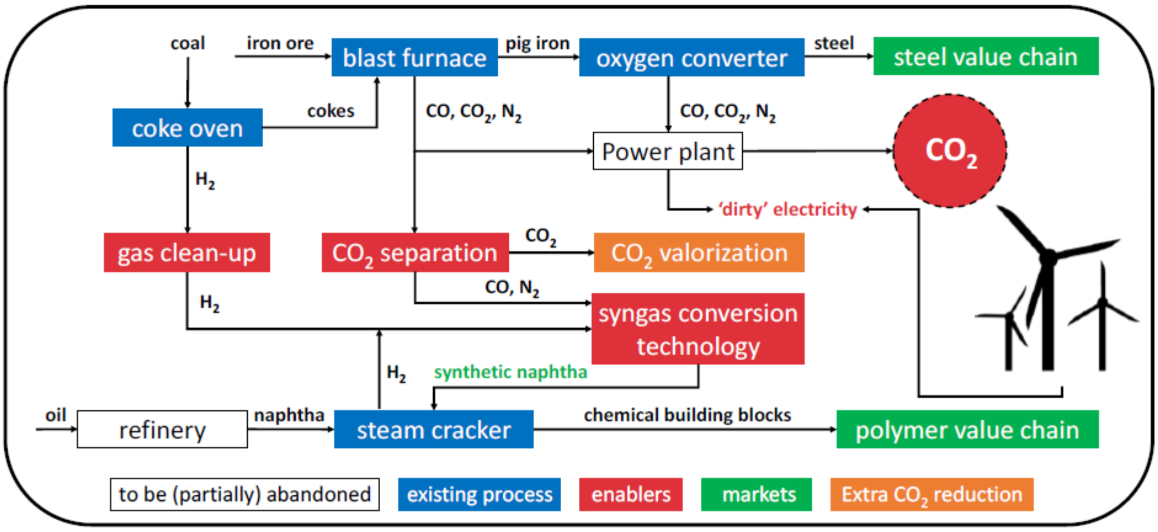


**Figure 17: Overview of the Steel2Chemicals project (Ruitenbeek, 2018)**

[50] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

For several processes there are multiple options that need to be further tested and integrated. For example, the reverse water gas shift should be demonstrated at scale and there are multiple options to do this. The integration of such new technologies with the steel and chemical processes also requires further development. Integration with refineries might be necessary depending on the product.

Another CCU option is the use of bio-fermentation to convert CO to ethanol and other chemicals. The Steelanol project between ArcelorMittal and Lanzatech in Ghent is targeting to demonstrate the yearly production of 80 million litres of ethanol, with the option to diversify to other chemical building blocks on the longer term.

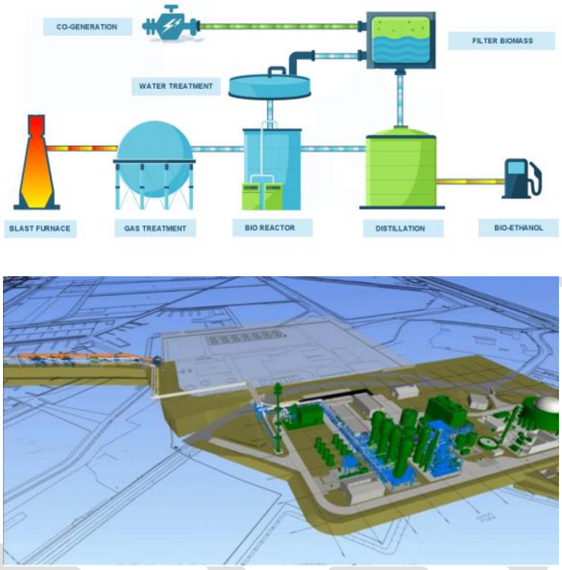


**Figure 18: Lanzatech process and demonstration plant (W. Van der Stricht 2019)**

### 6.9.4.1 Innovation objectives

- Develop the separate technologies
  - Development of N2 separation from TRL 2 to TRL 5 by 2025 and TRL9 by 2030
  - Development of impurity removal from TRL 5 to TRL 7 by 2025 and to TRL 9 by 2030
  - Development of CO gas conversion from TRL4 to TRL7 by2025 and TRL8 by 2030
- Integrate the technologies with locally available waste heat

### 6.9.4.2 Impacts

***GHG emissions***

Applicability (volume) to be evaluated 49.2 Mt CO/y (Dechema study p.101).

The potential of these technologies is determined by the available CO in Europe. As said earlier, most CO from the steel sector is used already in power generation. Industrial CO emissions to the atmosphere are estimated to be around 3.3 MtCO, of which steel is 2.1 MtCO (Berg, et al., 2018). These CO oxidises in the atmosphere to $CO_2$ and has a GHG impact there. This is calculated based on the molar weight ratio (44/28) to be around 5 MtCO2e.

If the CO streams would be shifted from power generation, the volumes of CO that could be used would be sufficiently higher. Dechema estimates the volume of CO at 49 $MtCO_2$/yr (DECHEMA, 2017). This equates to $CO_2$ emissions of 77 $MtCO_2$.

The emission reduction impact depends on whether fuels or chemicals are produced. When producing chemicals, the carbon can be recycled post-consumption. When producing fuels, the carbon is emitted during use. However, it would displace fossil fuels, and therefore would cut emissions by 50% (from emissions from both CO and from fossil fuel to emissions only from synthetic fuel).

***Waste***

The chemical valorisation of CO can effectively contribute to the development of a more circular economy  However, because $CO_2$ is a gaseous effluent it does not directly contribute towards the target of zero landfilling and water discharge.

***Competitiveness***

It is expected that this technology will be competitive when the renewable energy directive justifies a premium on produced fuels.

### 6.9.4.3 Programming

Development towards 2030

- Gas clean-up (take out impurities that have impact of down-stream conversion)
- Gas separation (improved CO2 removal, development of N2 removal technologies)
- Developing catalytic technologies to convert waste-based CO sources into valuable chemical products & fuels with improved performance (2nd generation catalysts)
- + Note: Life Cycle Assessments to assess overall CO2 impact (including heat integration and industrial symbiosis aspects)

Development towards 2050

- Optimisation of the concept and broad replication with different target products
- Optimisation of CO2 accounting over borders and industries (Development of a CO2 transfer mechanism)

### 6.9.4.4 Investment needs

For TRL 1-4 projects: 1-3 million per project

For TRL 5-7 projects: 10-15 million per pilot

For TRL 8: 100-150 million for a demo unit

*<<the estimation of how many projects are needed at each TRL and in each time frame for this innovation programme is to be added in the next version>>*

**Table 21: Investment needs in € million – work in progress and subject to change**[51]

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| **2020-2030** | | | | | | | |
| **2030-2040** | | | | | | | |
| **2040-2050** | | | | | | | |
| **Total** | | | | | | | |
| ***% public funding*** | | | | | | | |
| ***Public funding*** | | | | | | | |

### 6.9.4.5 Success factors

- Policy framework: recognition of CO2 emission avoidance in ETS

[51] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

- Life Cycle Assessments to assess overall CO2 impact (including heat integration and industrial symbiosis aspects)
- Hydrogen availability
- Incentive in the renewable energy directive for synthetic fuels

## 6.10 Disruptive processes for optimised use of virgin and secondary resources

### 6.10.1 Advanced catalysis providing raw material flexibility and lower energy inputs through alternative chemical pathways

#### 6.10.1.1 Innovation objectives

Catalysts allow chemical reaction to proceed at lower temperatures and with increased yield and selectivity. A catalyst accesses other chemical pathways than used by the non-catalytic reaction. The inherent change in chemical pathways will be particularly relevant for the next generation of catalysts that will need to work on the direct utilisation of renewable energy inputs in the form of electrons or photons, rather than heat generated from the combustion of fossil fuels. While traditional homogeneous and heterogeneous catalysts have been known for decades, there is still consider room for more than simple stepwise improvement. The recovery of homogenous catalysts is still an energy and resource intensive endeavour. Bio-inspired catalysis can access still unknown chemistries (e.g., direct, selective methane oxidation to methanol) and lead to improved selectivities. Heterogeneous catalysts can still be much better: more robust, longer lived, greater yields and higher selectivities.

Eventually, all the carbon we need for the chemicals and materials our society depends on for its standard of living will have to come from the carbon that is already around us, from $CO_2$, biomass and carbon products recycling (e.g. plastics). New catalysts will be needed to reach this goal, thus catalyst improvement will mainly be applied in the chemical industry, although the refineries sector will also benefit. Because of this required circularity, however, new catalysts will enable the improved cross-sectorial exchange of process flows through utilisation of secondary raw materials and better control of by-products from chemical reactions with varying, secondary raw material inputs. The most relevant example is $CO_2$ flows in H4C. The objectives are to develop:

- **Catalyst using renewable energy inputs directly,** specifically using photons or electrons directly from renewable energy sources to drive the reactions, thus increasing the conversion's energy efficiency. Photocatalysis and electrocatalysis also offer the possibility of developing efficient renewable energy storage vectors, such as traditional fuels or fuel substitutes (e.g., methanol or dimethyl ether)
  - **Photocatalysis**: New multifunctional catalysts that can harness the energy of the sun directly will provide breakthroughs in the production of value-added chemicals from simple, sustainable building blocks like $H_2O$ and $CO_2$. Advances will permit new combinations of compounds capable of undergoing cooperative redox chemistries, leading to radically new chemical processes for basic chemical building blocks
  - **Electrocatalysis**: Likewise, new catalyst/electrode constructs will permit the direct utilisation of electrons (electricity) directly from other renewable energy sources, using a variety of technologies. These electrocatalysts will make it possible to create carbon-carbon bonds without the use or loss of halogens, provide new routes to polymers and activate less reactive molecules.
- **Highly efficient heterogeneous catalysts**: Since heterogeneous catalysts are not in the same phase as the reactants, they have the advantage that they are easily separated from reaction products and reusable. However, heterogenous catalyzed reactions are generally less selective and have lower yields than homogeneous catalyzed reactions. Advances in the reactive control and selectivity of heterogeneous catalysts will improve energy and resource efficiency. Increasing the lifetime of heterogeneous catalysts will

reduce catalyst regeneration and replacement costs and plant downtime. The continuous replacement of heterogeneous catalysts for homogeneous catalysts will permit further process improvements, especially if the heterogeneous versions also offer the new chemistries expected from the greater adaptation of new classes of homogeneous catalysts.

- **Fully recyclable homogeneous catalysts**: Because homogeneous catalysts operate in one-phase systems, yield and selectivity are often high, but recovery of the catalyst after the reaction can be resource (solvent) and energy intensive. New homogeneous catalysts that can more easily be separated from the reaction products will provide significant advantages in resource and energy efficiency. New catalysts that are not dependent on critical raw materials can also lead to new and better chemistries. Examples are organocatalysts, enzymes, and biomemetic catalysts. Reproduction of the enzymatic function of methanotropic bacteria could provide a route to the direct conversion of methane to methanol.
- **AI/Machine learning tools to optimise discovery of new catalysts:** Catalysts operate in a multi-dimensional parameter space, where temperature, pressure, flow rates, and reactant and catalyst concentrations all play a role. In addition, the discovery of actual, active catalyst compositions also has a large number of permutations. For heterogeneous catalysts, the support, the phase and shape of the catalyst particles and the presence of additives on the support surface can all affect the reaction kinetics and play a role in the success of reaction. For homogeneous catalysts, similar parameters include the electron density of the metal, the type of ligands and the required excess of those ligands. Given a large enough data set, it will be possible to develop AI/machine learning tools to explore the catalyst/reaction parameter space and identify new, better catalysts for a host of different catalytic reactions.

For all catalyst development, the improved **catalysts need to be tolerant to impurities** (e.g., $SO_x$ and $NO_x$ or be able to use dilute $CO_2$ streams) to improve raw material flexibility and allow more streams to be processed/recycled without a need for upfront purification.

### 6.10.1.2 Impacts

Catalysts improve reaction efficiency and product yield and selectivity, thus leading to reduced GHG emissions via lower energy use and decrease in pollution through a decrease in reaction by-products. Increased stability, lifetime and recyclability will result primarily in increased competitiveness. Catalyst volumes are generally very small, although many catalysts contain valuable CRMs and some contain potentially environmentally harmful materials.

***GHG emissions***

| **Sector** | **Current Emissions in EU,** MtCO2e | **Emissions targeted by the IP,** % | **Reduction within targeted emissions,** % | **Emission reduction impact,** MtCO2e |
|---|---|---|---|---|
| Cement | 105 | 0% | 0 | 0 |
| Steel | 190 | 0% | 0 | 0 |
| Chemicals | 128 | 100% | 15%[52] | 19 |
| Ceramics | 17 | 0% | 0 | 0 |
| Non-ferrous metals | 18 | 0% | 0 | 0 |
| Minerals | 19 | 0% | 0 | 0 |
| Water | 27 | ? | | |
| **Total SPIRE-CCNI** | | | | |

[52] Estimate, based on (IEA, 2013), assuming that around half of the catalyst and related process improvements would be the consequence of catalysts.

***Waste***

| Sector | Type of waste (e.g. plastics) | Current amount of waste, Mt | Waste targeted by the IP, % | Reduction within targeted waste, % | Waste reduction impact, Mt |
|---|---|---|---|---|---|
| Cement | None | | | | |
| Steel | None | | | | |
| Chemicals | Alumina's, silicas, oxidised materials | Not known | 1-5% | 90% | [53] |
| Ceramics | None | | | | |
| Non-ferrous metals | None | | | | |
| Minerals | None | | | | |
| Water | | | Not known | | |
| **Total SPIRE-CCNI** | | | | | |

***Competitiveness***

If these innovations would be developed, industries' efficiency increases, which is beneficial for its competitiveness.

### 6.10.1.3 Programming

For all catalysts, the aim is to optimise the yield and selectivity they deliver at as easy-to-achieve-as-possible process conditions (lower activation energy), while being stable during a long lifetime (no/very limited fouling and loss). The new catalyst will also need to be fitted to handle new feedstocks and energy sources for the transition of the chemical industry.

- **Photocatalysis** is still at TRL 3, with the aim to be at TRL 5 in 2024. Even then, significant development will be needed to scale-up and industrialise these processes. Since this is the least developed catalytic area, there is a need for a broad catalyst development programme that will address a range of different technologies. Nanotechnology is at the forefront of these technology developments, since it is essential to control both the formation and eventual reaction of both electrons and holes generated within the photocatalyst. The technological programme will need to address the following needs:
    - Synthesis of scalable, inexpensive and robust photocatalysts that are stable over long reaction times;
    - Photocatalyst development today requires the introduction of very pure reactant streams, to ensure that the photocatalyst is actually reacting with the desired substrate and not advantageous impurities. New catalysts therefore need to control the reaction of impurities in the feed streams;
    - Photocatalysts that can access as much of the solar spectrum as possible, to increase efficiencies;
    - Catalysts that have highly efficient electron and hole generation, inhibit their recombination and do not need sacrificial reductants for regeneration.

[53] This waste reduction could be achieved simply by reducing the number of catalytic cycles, which would lead to a higher energy penalty. The goal is to reduce the waste generation without decreasing the turnover frequency of state-of-the-art catalysts.

- **Electrocatalysis** is in most cases at a low TRL today, with the aim to be at TRL 5 in 2024. New to be developed catalyst can enable more selective robust and coupled oxidations and reductions:
    - Novel technologies such as microwaves, plasma and ultrasound (refer to innovation programme, “Other electricity based heating processes”) will likely not operate with the already existing catalysts, so to implement these, new catalysts need to be developed, starting in many aspects from ground zero, as different bonds need to be activated, and different process and catalysts are needed to do so effectively;
- As with photocatalysts, significant development will however still be required to realise the industrialisation of electrocatalytic processes. As opposed to photocatalytic processes, there are a few electrocataytic processes in industry, but there are by far the exception rather than the rule. Examples of required developments include the following:
    - More selective, robust and cooperative oxidations and reductions;
    - The development of new electrodes designed at the nanoscale, for direct catalytic function at the electrode surface;
    - The development of hybrid electrode/homogeneous catalyst solutions to improve yield and selectivity;
    - New non-CRM based, high performance and long-lasting electrocatalysts;
    - Development of better electrocatalysts for the valorisation of biomass
    - Bio-electrocatalysis/microbial electrosynthesis for targeted conversions and improved productivity;
- **Heterogeneous catalysts** are already used in industry. About 80% of all catalytic processes are heterogeneous because of the processing advantages of heterogeneous catalysts. However, there are still significant advances that need to be made to introduce the required new chemistries to reach the sectors' 2050 goals. Some examples of the advances in heterogeneous catalysts required:
    - 3-D printing of heterogeneous catalysts, that will improve conversion and selectivity and reduce production costs;
    - Leach-free heterogeneous catalysts with the same activity as the state-of-the-art, to reduce purification steps and reduce waste;
    - Development of catalysts for the direct conversion of methane to chemicals;
    - Development of new catalysts for the valorisation of biomass (e.g., lignocellulose) that are tolerant to feedstock variability.
- **Homogeneous catalysts** are already used in industry. About 20 % of all catalytic processes are still homogeneous, as a heterogeneous version that provides the same yield and selectivity has not yet been found. As with heterogeneous catalysts, there is still much to be done. Some examples:
    - Immobilised organometallic catalysts for flow reactors will reduce waste and increase catalyst stability and recycling while still accessing the well-understood and well-functioning organometallic reaction mechanisms;
    - Development of new catalysts for the valorisation of biomass (e.g., lignocellulose) that are tolerant to feedstock variability;
    - Bioinspired catalysts such as biomimetic catalysts and naturally occurring and artificial enzymatic catalysis that allow the valorisation of new chemistries such as depolymerisation and methane activation;
    - Methods to make enzymatic catalysts more stable and robust under non-biological reaction conditions;
    - New catalysts based on abundant, first-row transition metals and that provide new C-C and C-H functionalisations for waste reduction and better competitiveness;

  - Cooperative/cascade catalytic reactions combining multiple homogeneous or heterogeneous catalysts for improved processing.
- The development of AI/machine learning for catalyst prediction will need both the generation of large data sets and the development of predictive software. It is expected that this development reaches a stage where it becomes another tool in the catalyst development toolbox rather than a rolling set of innovations for the other catalyst programming activities. Some examples of where initial efforts can be made:
  - Rational design and prediction of porous catalyst supports for better stability and recyclability;
  - Design of novel enantioselective catalysts;
  - Linking of catalyst development and process improvement.

The programming to develop catalysis tolerant to impurities (e.g. $SO_x$ and $NO_x$ and able to process dilute $CO_2$ streams) is covered by the programming of homogenous and heterogenous catalysts.

### 6.10.1.4 Investment needs

**Table 22: Investment needs in € million – work in progress and subject to change[54]**

| Technology: | Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total: |
|---|---|---|---|---|---|---|---|---|
| **Photocatalysis** | 2020-2030 | 35x €2,5 | 15x €2,5 | | | | | |
| | 2030-2040 | | 15x €2,5 | 6 x €12 | | | | |
| | 2040-2050 | | | | 3 x €25 | | | |
| | ***Total*** | | | | | | | |
| **Electrocatalysis** | 2020-2030 | 35x €2,5 | 15x €2,5 | | | | | |
| | 2030-2040 | | 15x €2,5 | 6 x €12 | | | | |
| | 2040-2050 | | | | 3 x €25 | | | |
| | ***Total*** | | | | | | | |
| **Highly efficient heterogeneous catalysts** | 2020-2030 | 25x €2,5 | 8 x €5 | 5 x €12 | 2 x €25 | | | |
| | 2030-2040 | 25x €2,5 | 8 x €5 | 5 x €12 | 2 x €25 | | | |
| | 2040-2050 | | 8 x €5 | 5 x €12 | 2 x €25 | | | |
| | ***Total*** | | | | | | | |
| **Fully recyclable homogeneous catalysts** | 2020-2030 | 20x €2,5 | 6 x €5 | 3 x €12 | 1 x €25 | | | |
| | 2030-2040 | 20x €2,5 | 6 x €5 | 3 x €12 | 1 x €25 | | | |
| | 2040-2050 | | 6 x €5 | 3 x €12 | 1 x €25 | | | |
| | ***Total*** | | | | | | | |
| **Coupling of machine** | 2020-2030 | 15x €4 | 5 x €5 | 3x €10 | | | | |



[54] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **learning/IA and high throughput technologies for catalyst development** | 2030-2040 | 10x €4 | 3 x €5 | 1x €10 | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | €500 | €400 | €472 | €375 | €0 | €0 | €1747 |
| | *% public funding* | | | | | | | |
| | ***Public funding*** | | | | | | | |

Non technological aspects: As the core technology is well developed, there is no need for education/training programmes.

#### 6.10.1.5 Success factors

Even though catalysts have been developed and used for many decades, new disruptive opportunities like photocatalysis and biologically-inspired catalysis (such as enzymatic and biomemetic approaches catalysis) continue to emerge, and their further development thus enables the transition and makes the transition more efficient – reducing the need for scarce goods such as renewable energy.

### 6.10.2 Complete reuse of water and valorisation of the materials contained

#### 6.10.2.1 Innovation objectives

The composition of waste water varies strongly between different industries/plants. Therefore, there is no “one size fits all” solution. Moving increasingly towards a bio-economy may well cause an increase of waste water, thus making adequate treatment even more important.

The focus of wastewater treatment technologies has always been on cleaning the water without too much regard for the impurities dissolved in it. This focus needs to be changed to recovering as many valuable components dissolved in the water as possible. Waste water treatment will therefore be reimagined by applying separation/recycling steps where possible on concentrated waste streams directly derived from process outputs, thus avoiding mixing all streams together and then applying all separation/recycling steps on the combined streams. This requires and allows for new “fit for purpose” technologies, while there will also remain a need to apply technologies with broad functionality.

Several objectives have been defined to enable increased/full recycling of waste water and its components:

- **Recycling of solubles from effluent treatments.** Innovative conversion technologies that can valorise solubilised compounds to valuable chemicals, e.g., microbial production by fermentation or microbial conversion to polymers, need to be developed. Materials to be recycled would include components such as phenols and micro pollutants (avoiding the discharge of these toxic chemicals). As low substrate concentrations lead to low product concentrations and the concentration of high amounts of wastewater is not feasible, technologies that concentrate reactants or products are also needed. The ambition is to have 25% of solubles recovered from wastewater by 2025 and 90% by 2050.
- **Recycling of solids from effluent treatments into new materials or reuse for energy production.** This includes recovery of organics for reuse and, if necessary, biogas production and eventually energy production, inorganics (phosphates and nitrates for application in fertilisers) and trace metals/materials (e.g., magnesium, calcium, precious

metals). The aim is to recycle 50% of the currently unused (in)organic solids by 2030 and to strive towards 100% by 2050, thus eliminating landfilling, reducing feedstock cost with cost-effective production processes from waste streams.

- **Developing optimised effluent treatment for freshwater substitution** to allow full recycling of waste water. This reduces the uptake of fresh water, which is expected to become increasingly scarce in Europe with water shortages in summer; the aim is that applying new technologies will enable a 40 % acquisition of fresh water from the wastewater treatment plant in 2030 and fully in 2050.
- A fourth objective is to develop **alternative processes with reduced water use**, such as solid-state fermentation with increased yields for the production of chemicals without presence of free water and electrification to replace steam heating.

#### 6.10.2.2 Impacts

***GHG emissions***

The GHG emissions of waste water treatment have not been assessed, but new technologies should cause no/low GHG emissions, by for example applying renewable electricity where feasible.

***Waste***

Currently, solids and soluble components are still relegated to landfill after incineration, and waste water is discharged rather than recycled.

***Competitiveness***

Currently, solids and soluble components are still relegated to landfill after incineration, and waste water is discharged rather than recycled.

The competitiveness of technologies differs per application, but a few trends can be observed:

- Valorisation of secondary materials reduces virgin material- and energy-needs, thus cost;
- Re-using currently discharged materials increases Europe's resource independence; for example, the amount of phosphates currently discharged in water is twice the European phosphate consumption – currently mainly imported from Russia and Morocco);
- Full recycling of waste water would lead to high costs – which innovations should bring down.

Achieving near zero water discharge could, without innovations, be costly, but needed (in some places) with limited availability of fresh water. Valorising components in the water can be competitive in specific cases.

#### 6.10.2.3 Programming

There is potential to improve current separation, because:

- Often a purge (losing water and components) is needed to avoid accumulation of trace materials;
- Separation leads to GHG emissions, for example aeration requires much more energy than treatment with oxygen (available from the production of green hydrogen) would;
- Separation is often organised at cluster level, while to meet the needs to treat locally (directly at the output of a plant) where possible, significantly cheaper smaller scale modular treatment systems for decentralised treatment will need to be developed for all innovation objectives;
- Separation of solutes needs innovative technologies that combine their conversion to value-added chemicals with their accumulation for effective harvesting.

The following activities are foreseen:

- **Developing optimised effluent treatment for freshwater substitution** using the optimal combination of chemical and biological treatment methods, with general application of aerated granular sludge (AGS) technology, leading to significant improvements in treatment intensity, energy consumption and land use (TRL7-9), The approach should:
    - Use a strong multidisciplinary approach using integrated real-time (bio)process control and monitoring (TRL 4-6),
    - Make use of artificial intelligence for smart process control (TRL 1-3)
    - Apply an integrated treatment of complex industrial wastewaters by membrane technology (TRL 4-6)
    - Generate new treatment technologies, e.g., hybrid membrane systems (TRL 3-5) for water treatment increasing synergy between membrane systems and active sludge systems, oxidation, adsorption, coating, etc. Improvement of advanced oxidation and adsorption/absorption technologies (TRL 5-7). (e.g., active carbon, ozonation) (WssTP, 2017);
    - Include innovative biological nutrient (nitrogen, phosphorous) removal processes for energy efficient treatments (TRL 4-6).
    - Consider optimal cascading of water streams and optimise the energy content (temperature) of the water streams, including increasing energy production from water sources (TRL 6-8) and/or energy recovery in water flows through efficient turbine technologies (WssTP, 2017);
    - Evaluate and reduce the ecological impact (using whole effluent toxicity testing);
    - Develop Life Cycle Analysis methodologies to compare emerging technologies and pilot applications for water in the value chains of the process and manufacturing industries;
- **Recycling of solids from effluent treatments into new materials or reuse for energy production** and **recycling of solubles from effluent treatments** with innovations including:
    - The valorisation of cellulose toilet paper residues in the wastewater by e.g. sieving out cellulose fibres (TRL 4-6) or by their fermentative conversion to bioethanol,
    - Valorisation of industrial brines (TRL 6-7) (WssTP, 2017), which could lead to substantial volumes of valuable organic elements, such as P (currently captured with struvite ($Mg(NH_4)(PO_4)$) – after which it is inert and no longer apt for plant uptake, while technologies to purify using iron, magnesium/calcium that allow recovery of 60% of the phosphate are now at TRL 5), N, K, and Mg for different types of fertilisers. Moreover, brines can be reused as sources for salts, minerals, nutrients, acids and alkalis but also for salty aquatic cultures (algae and fish).
    - Production of large quantities of membrane and modules (TRL 6-8), reducing the production costs through economy of scale, and scaling-up and integrating modules in large systems; chemical free membrane operation and relation to pumping costs (WssTP, 2017);
    - Integration of electrochemical technologies for industrial waste valorisation: electrodialysis (mono and bipolar technologies metathesis) recovery of chemicals (acids and alkalis); development of low cost technologies for efficient separation of interferences (WssTP, 2017);
    - Intensified water purification/filtration concepts (TRL 3-5) based on nano-structured, nano-functionalised membranes and nano-film deposition for micro-pollutants and virus removal. The development of new membranes with increased lifespan and lower cost (TRL 1-3) (WssTP, 2017);
    - Recovery of alginates as value-added products by extraction from granular sludge (TRL4-6);
    - Biological phosphorous accumulation with agricultural application potential;

- Biochemical engineering technologies that apply fermentation technology to convert toxic phenols by reversible immobilisation of microbial cells for intracellular product accumulation (microbial oil for e.g. biodiesel production, or polyhydroxyalkanoates bioplastics) and its recuperation from wastewater flow systems (TRL 2-3);
- Development of highly effective photocatalytic technologies for controlled conversion of micro-pollutants (emerging pollutants) to desired products instead of unknown degradation products (TRL 1-2).

- For **alternative processes with reduced water use:**
  - New energy-efficient measures (TRL 6-7) reducing the use of cooling water and its impact on water systems;
  - No other activities have been defined yet.

Overarching (WssTP, 2017), waste water management benefits from improved measurement, which, when combined with new digital solutions can deliver:

- Autonomous monitoring in water networks, energy/heat harvesting and reuse from water, optimisation of water use in cooling/heating in process industries (TRL 6-8);
- Demand forecasting for efficient network, buffer and pumping management (TRL 6-8);
- Water recycle/reuse processes and loops with continuous water quality control, process feedback loops and process control;

To improve the measurements the following should be developed:

- New cheaper sensors for detection and chemical measurement of pollutants (TRL 1-3 or 3-6, depending on pollutant), with increased stability and longevity;
- Sensors and sampling techniques to detect indicator pollutants (or groups, including biological) and to measure specific compounds;

The foreseen activities would benefit from the development of new, better catalysts, as described in the Innovation Programme, "Advanced catalysis providing raw material flexibility and lower energy inputs through alternative chemical pathways".

#### 6.10.2.4 Investment needs

*<< This will be added after the stakeholder consultation >>*

**Table 23: Investment needs in € million – work in progress and subject to change**[55]

| Technology: | Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total: |
|---|---|---|---|---|---|---|---|---|
| **Developing optimised effluent treatment for freshwater substitution** | 2020-2030 | | | | | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Recycling of solids from effluent treatments into** | 2020-2030 | | | | | | | |
| | 2030-2040 | | | | | | | |

[55] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **new materials or reuse for energy production** | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Recycling of solubles from effluent treatments** | 2020-2030 | | | | | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Develop alternative processes with reduced water use** | 2020-2030 | | | | | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| | **TOTAL** | | | | | | | |
| | *% public funding* | | | | | | | |
| | ***Public funding*** | | | | | | | |

#### 6.10.2.5 Success factors

- Municipalities investing in new water treatment plants to recover valuable, recyclable materials.

### 6.10.3 Innovative processes to maximise use of secondary raw materials

In many cases, virgin resources have either restricted availability, come from politically unstable regions or have a high environmental footprint from their extraction and processing. Nevertheless, on average, only 12% of the material resources used in the European Union in 2016 came from recycled and recovered materials and saved extraction of primary raw material, while overall around 55% of all waste excluding major mineral waste was recycled (Eurostat, 2019, March 4). The objective of this innovation programme is to significantly improve this percentage.

Key challenges that hamper optimisation of use of secondary resources are:

- Insufficient appropriate methods (technical and economic) for treating process residues for internal or external recycling
- Recycling/material recovery technologies are too expensive
- Secondary materials have varying composition and quality and current processes are not flexible enough to integrate and process recycled resources with varying properties
- Develop the appropriate and cost-effective methods and techniques for treating process residues and waste streams

This innovation programme focuses on developing the technologies that enable recycling of material flows both inside the sector where the material was produced, or in another sector. To achieve this, in some cases new technologies are needed to valorise the waste. This IP focuses on the technologies that are within the SPIRE-CCNI scope. This means that only the technologies needed to valorise the waste through the process industries are considered. If a waste flow can be valorised without the process industries (for example, mechanical recycling of plastics directly in the manufacturing industry) that is not in scope.

It should be highlighted that any type of waste is in the scope, including: Construction and Demolition waste (CDW), Waste Electrical and Electronic Equipment (WEEE), Municipal Solid Waste (MSW), Packaging waste, Automotive waste, etc.

The innovation needs differ per sector:

**Cement**

A high share of demolition waste is already recycled. Technologies have been developed to permanently capture $CO_2$ in these recycled materials. These technologies are supported already by innovation programme 6.8.2 Circular construction materials by re-carbonation. The German cement sector already uses about 18% secondary raw materials.

**Ceramics**

A small share of ceramic material can be reused in making new ceramics today, and this share differs from application to application. Most end-of life ceramic are found in Construction and Demolition waste, mixed up with other materials. To avoid landfilling and to valorise materials already landfilled, technologies are needed to separate them from components which are prejudicial to the ceramic process. If the adequate technologies are developed, all ceramics currently landfilled could be reused to make new ceramics. In addition, it should be noted that the ceramic sector also has a wide potential to use non-ceramic waste as feedstock.

**Chemicals**

Of the wide range of materials produced by the chemicals sector, the predominant material stream in waste is plastics. In 2018 about 30 million tonnes of plastic waste was generated in the EU, of which 26% was recycled (Global Plastics Alliance, 2018). To be able to also recycle other plastic streams, new technologies are required. Plastic waste can be recycled using mechanical and chemical recycling. Mechanical recycling entails the melting of plastics into new products. Chemical recycling entails the process in which plastics are broken down into the chemical building blocks that subsequently can feed into the chemical industry to be turned into new plastics. Some technologies also enable the conversion of biomass into chemical building blocks. For chemical recycling technologies more innovation is needed. A specific area where innovation is needed is in the field of plastic composites (different plastic types combined in one product).

Fertilisers can be recycled from the ground water (ammonium nitrate) or by capturing and recycling ammonia from manure. Pharmaceuticals, which are complex to make, are now often not recycled, and either end up in the waste, or in the waste water.

**Steel**

- Most steel is recycled today in Europe, but scrap cannot yet be upgraded to the same quality as can be achieved with primary steel. For some by-products of the steel sector useful applications are sought for. Slags are currently being used in building materials, but more applications are needed. Sludges can currently not be recycled because it contains too much ZnO. The produced CO can be used CCU applications (innovation programmes  Multi-criteria analysis in a standardised manner to evaluate the impact of technologies for various applications
- Access to low-carbon hydrogen or electricity at competitive prices
- Cost-effective $CO_2$ capture and purification technologies (see innovation programme 6.7.1 Flexible $CO_2$ capture and purification technologies)
- Policy framework for applications (chemical, transport, energy storage)

$CO_2$ (and $CO_2$/CO) to polymers and 6.9.4CO captured from industrial waste gases to chemicals and fuels)

**Aluminium**

Thanks to its intrinsic economic value, aluminium scrap is already well collected and recycled from Buildings (about 90% Recycling rate), from automotive (about 90%) and appliances. There are still room for improvement in packaging market (60-70% recycling rate). In all cases, moving to higher quality recycling is beneficial, especially in the future since aluminium supply will be more based on recycling.

**Other non-ferrous metals**

Scrap (pre-)processing for improving scrap quality (cooperation ferrous and nonferrous sectors) is needed. For the removal of metallic coatings of tin and zinc limited economically viable solutions based on hydrometallurgy or thermal treatment are currently available. Separation of scrap through the application of advanced physical separation techniques (e.g., sorting, shredding, size, and density classification) should be further developed. Treatment of residues from ferrous and nonferrous sectors (dusts, slags, and sludges) as well as residues from the energy producing sector (ashes, slags from waste incineration) for an increased recovery of valuable metals, such as iron, zinc, copper, chromium is possible by exploring pyro- or hydrometallurgical as well as mechanical/physical treatment routes.

Up to now, a share of residue coming from ferrous and nonferrous metal production and from waste incineration are landfilled; however valuable metals could eventually be recovered by means of appropriate technologies.

Metal demand in the field of electronics is increasing. The recovery of valuable metals from electronic waste can be achieved with physical, chemical, biological methods or combinations thereof. Bioleaching, involving microorganisms, is working at near ambient temperatures, with positive environmental performance attributes for metal recovery processes.

**Other minerals**

Recycling rate of industrial minerals at product level is up to 50%. This value strongly depends on the recycling rate and implementation of the EU directives with focus on the waste management. Most minerals are being transformed into other materials, and at the end of life are recycled back into that transformation project, thereby no longer involving the minerals sector as user of the recycled material. Phosphorus (P) is one of the critical resources prioritised by the EC. Significant efforts and priority funding were focused on developing materials and technologies for P recovery from secondary P rich sources, such as sewage sludge from wastewater treatments.

#### 6.10.3.1 Innovation objectives

There is significant potential to improve this use, for which the following innovation objectives have been defined:

- **Developing separation/sorting technologies** that can remove impurities prior to the process to minimise use of raw materials and allow processing of all secondary materials. There are two different mechanisms:
    - Remove impurities prior to the process so that the secondary raw material can be processed to perfect quality again (aluminium recycling)
    - Sorting out waste that doesn't need processing for direct application as a secondary raw material in a process (e.g., clinker substitution in cement production)
- **Recycling within the same sector**, this includes increased 1:1 recycling (recycling of aluminium) in cooperation with the recycling sector, and reuse of by-products/off-spec material/waste from the own sector.
- **Other recycling options**;

- **Digital solutions to enhance processing of secondary raw materials** as enabler. As the quality of the secondary input materials will likely continue to vary significantly over time, online sensing, monitoring and proactive adjustment of the production process to secure the production of on-spec products will enable more use of secondary raw materials.

### 6.10.3.2 Impacts

***GHG emissions***

The increased use of secondary raw materials achieves two primary objectives:

- An increase in the use of secondary raw materials *a priori* implies a reduction of the use of primary raw materials. Concurrently, there is a **significant reduction in waste and landfilling**, as materials previously landfilled are reused;
- There will be significant energy savings and reductions in **GHG emissions**, as the processing of secondary raw materials is generally less intensive than the processing of ores and minerals to produce primary raw materials, as seen in the aluminium and steel sectors. Indeed, reaching the goal of a carbon-neutral European society becomes much easier with a significant increase in the use of secondary raw materials. Increased use of secondary raw materials has clear cross-sectorial applications, as all SPIRE-CCNI sectors will benefit from the reuse of processed materials either within their own sectors or across the sectors.

*<<This will be compared with the still unpublished report Study and Portfolio Review of Cluster of Projects on Industrial Symbiosis in Directorate Prosperity (former Industrial Technologies) in DG R&I: Findings and Recommendations by Klaus Sommer. The results will be included here after publication and compared against the bottom-up numbers.>>*

***Waste***

*<<the below table is to be completed after the stakeholder consultation>>*

| **Sector** | **Type of waste (e.g. plastics)** | **Current amount of landfilled waste,** Mt/year | **Waste targeted by the IP, %** | **Reduction within targeted waste,** % | **Waste reduction impact,** Mt |
|---|---|---|---|---|---|
| Cement | | | | | |
| Steel | | 4 kg blast furnace slag/tonne hot metal (primarily Zn and Pb)<br><br>±40% Hot metal desulphurisation slag<br><br>±9 kg dusts/tonne liquid steel | | | |
| Chemicals | | | | | |
| Ceramics | | | | | |
| Non-ferrous metals | | 200 Mtonen (wet waste with very fine particles) | | | |
| Minerals | | | | | |
| Water | | | | | |
| **Total SPIRE-CCNI** | | | | | |

*<<This will be compared with the still unpublished report Study and Portfolio Review of Cluster of Projects on Industrial Symbiosis in Directorate Prosperity (former Industrial Technologies) in DG R&I: Findings and Recommendations by Klaus Sommer. The results will be included here after publication and compared against the bottom-up numbers.>>*

***Competitiveness***

*<<This will be compared with the still unpublished report Study and Portfolio Review of Cluster of Projects on Industrial Symbiosis in Directorate Prosperity (former Industrial Technologies) in DG R&I: Findings and Recommendations by Klaus Sommer. The results will be included here after publication and compared against the bottom-up numbers.>>*

#### 6.10.3.3 Programming

The programming is following the logic of the objectives.

**Developing separation/sorting technologies** - This includes bio-separation, reactive separation, hybrid separation and electrochemical separation of materials (incl. catalysts). Per sector the following waste stream challenges have been identified for which the innovations will be identified/developed:

*Steel*

- There are (sometimes toxic) impurities (molybdenum, chromium, zinc) in scrap that need to be separated off and for which an application would need to be found (to prevent landfilling them); basic oxygen converter dust contains iron.

*Chemicals*

- The quality of waste streams is an important enabler of (mechanical and chemical) plastics recycling.

*Cement*

- Ashes from fuel combustion, sewage sludge and construction and demolition waste are often used as secondary material in the production of cement.
- The potential for waste product use is influenced by the raw materials available near the cement plant, which can vary significantly from site to site.
- High concentrations of silica, alumina, magnesium or sulphur can hinder large-scale use of alternative decarbonated raw materials, and the presence of volatile organic compounds (VOCs), trace elements content or variable compositions may cause further restrictions in some cases.
- Further preparation steps, as is the case of concrete crusher sand, may improve the quality of the material, but will also increase costs.

*Ceramics*

- An important step for recycling CDW as feedstock in ceramics is the sorting/separation of the different types of materials. Technologies (for example by using artificial scanning such as in glass recycling) are needed to improve the separation of the wastes that cannot be used in ceramic manufacturing (i.e. metals, gypsum which are prejudicial for the process) from the rest.
- In many cases recycling is impossible, due to the presence of prohibitive elements. By being able to separate these out, the potential use of secondary materials would increase significantly.
- Also, as different valorisation routes can be developed depending on the type of CDW, adequate sorting is very important. For instance, CDW with roof tiles, marble, slate, concrete, bricks, ceramic tiles, sanitaryware and glass can be recycled in ceramic

products and wood wastes could be recycled in the manufacture of isolating ceramic bricks or in expanded clays, but technologies to sort them are needed.

*Aluminium*

- Increasing recycling rates requires innovation in the collecting and sorting of used aluminium, to ensure that every piece of metal is recovered. Thus, technologies to support/promote the following activities are needed:
    - Maximising and optimising scrap collection system all over Europe for all markets/products
    - Implementation of a smart recycling value chain, in particular advanced sorting technologies like LIBS.
    - Advanced sorting for household waste/packaging (e.g. Eddy-current separation and LIBS technologies) for maximising high recycling rates and quality of recycled aluminium.
    - Bottom ash treatment to recover metals when household waste has been incinerated.
    - Develop alloy-based sorting technologies at affordable cost, e.g. by using X ray technologies (Aluminium, 2016);
    - Develop new mechanical and/or chemical processes for the recovery of salt, aluminium oxides and aluminium metal from salt slag (Aluminium, 2016);
    - Develop low-cost process for melt purification including application for possible by-products, e.g. techniques to remove some specific impurities like Mg, Fe, Pb, Li, Si, Ti (Aluminium, 2016)l

**Recycling within the same sector -** Per sector the following waste stream challenges have been identified for which the innovations will be identified/developed:

*Steel*

- Innovative collection and sorting technologies (e.g., robotic cutting and handling or laser induced breakdown spectroscopy to allow automated sifting of mixed waste streams)
- Purification of molten scrap steel (e.g., sulphide matte, chloride slagging, preferential melting)
- New processes (e.g., belt casting, dust, sludge and slag treatment for separation of valuable materials)
- New product design reducing the use of unwanted elements or enabling easier separation
- Innovative technologies for characterisation (sensors, smart software tools) of steel scrap
- Better separation technologies, like for the de-zincing of coated steel sheets

*Chemicals*

- There are several technological routes for chemical recycling, and at this low stage of development it is not clear which routes offers most potential. Therefore, this innovation programme aims to develop all routes further to a maturity level where selection of most promising technologies is possible. The various routes are:
    - Electrochemical – this option is already included under innovation programme "Electrochemical conversion" because it uses electricity to drive the reaction.
    - Pyrolysis – this option uses very high temperatures to break down the material. The pyrolysis technologies are in TRL 7-9. Challenges are related to making the technology more robust for fluctuating waste composition.
        - Potentially still at a lower TRL, this technology could perhaps be electrically driven (refer to Innovation Program "Other electricity-based heating processes");

  - Gasification – this option converts plastic waste into syngas that can be used for various applications. Gasification technologies are in TRL6-9. Challenges are related to making the technology more robust for fluctuating waste composition.
    - Potentially still at a lower TRL, this technology could perhaps be electrically driven (refer to Innovation Program "Other electricity-based heating processes");
  - Depolymerisation – this option is used for certain types of plastics where polymers need to be separated from non-polymers. For PET the technology is at TRL6 and for some other promising plastics it is at TRL3
  - Biotechnological – in this route enzymes or microbes are used to break down the materials.
  - Solvolysis – this process can be used to separate composite plastics chemically using solvents. This technology is at TRL6.
- Note that technologies that turn $CO_2$ into chemicals can also be considered as recycling, but these are not considered here as they are already part of the innovation programmes: 6.9.1 Direct utilisation of sunlight (Artificial photosynthesis) and 6.9.2 Catalytic conversion of $CO_2$ (excluding photocatalytic and direct use in polymers).
- To develop the various routes, different technology development tracts should run in parallel. Since various options should be explored, five demo projects are foreseen of about €12 million each. Then, three additional demo projects will focus on more complex feedstocks, €25 million each.

*Cement*

- These technologies are supported already by innovation programme 6.8.2 Circular construction materials by re-carbonation.

*Ceramics*

An important pre-treatment step is the crushing and milling of the CDW prior to their use in ceramic materials. This is already being done with hard wastes from the own-ceramic process such as fired scrap, so these technologies should be adapted for the pre-treatment of CDW and improved to reduce their energy consumption, thus increasing recycling options of CDW into ceramic materials. The LifeCeram project aims to develop tiles that can incorporate waste produced during the production of tiles and other waste from the ceramic sector (LifeCeram, n.d.).

*Non-ferrous metals*

Standard technologies of metal recovery have achieved a TRL of 6-7 while bioleaching is at TRL 3-4. Thus, demonstration activities are needed for the later one to reach TRL 7-8 by 2030.

**Other recycling options** - Per sector the following waste stream challenges have been identified for which the innovations will be identified/developed:

*Steel*

- Sludge from the second stage of the blast furnace gas treatment is enriched with iron, carbon, zinc and lead. The iron and carbon-rich fractions are recycled within the plant, but the remaining part, about 33 % and containing zinc and lead, is landfilled;
- Basic oxygen converter gas dust containing up to 15 % wt zinc and 50 wt % iron: currently 12 w% is land filled; the iron contained can currently not be used in the steelmaking process anymore;
- Dust from the electric arc furnace (10 – 30 kg/tonne of liquid steel) containing up to 50 w% iron, which cannot be reused to produce steel with the state of the art Waelz process); the share of landfilling is constantly decreasing (now 34%).

*Chemicals*

- Gypsum ($CaSO_4$) is a by-product from the amongst others phosphate industry, and is either used for gypsum (building plasters), or land-filled; when other applications, or other process routes (for example recycling of phosphate), or when better purification processes (currently impurities might hinder the use in building plasters) would be developed this would no longer be necessary.

*Ceramics*

MSW can also be potentially valorised into the ceramic process. However, technologies should be developed or adapted to increase valorisation options of MSW into ceramic products, by eliminating prejudicial compounds (soluble salts):

- When using incineration, a process for an adequate washing of the fly and bottom ashes should be developed in order to eliminate soluble salts. This process can increase substantially the valorisation options and the percentage of use in ceramic products (roof tiles, bricks and floor tiles).
- Changing from traditional incineration to plasma inertisation would lead to a radical decrease of the volume of wastes (the wastes arising from plasma inertisation are formed by sintered agglomerates instead of fly ashes) and would also increase the possible recycling of these wastes, as they could be used in ceramic products (or even in glass-ceramics).

*Lime*

- Unconverted lime from for example flue gas cleaning applications or slag can be re-carbonated and then used as filled; this CCU process is already described under $CO_2$ mineralisation. The process resembles natural re-carbonation, but obviously at a much higher speed.

*Aluminium*

- At the aluminium smelt, 20 kg carbon waste is produced per ton primary aluminium. Most of this waste comes from the pot lining. This waste is only partially reused.
- In the RemovAl project (RemovAl, n.d.), the applicability of bauxite residue is as secondary material is increased by:
    - Reducing alkali content below 0,5 w%
    - Processing it into a soil stabiliser for civic works applications
    - Thermally treating it into light weight aggregates and high-performance binders
    - Processing it with other industrial by-products in a microwave furnace to produce metallic iron
- Valorising slags/sinters (RemovAl, n.d.).
- Use bauxite residue as ingredient for products (for example construction products) (Aluminium, 2016).
- Develop technologies to convert bauxite residue in valuable resources, e.g., extracting critical raw materials (Aluminium, 2016).

*Non-ferrous metals*

Around 200 million tonne per year landfilled sludge contains many very fine particles that are difficult to dry. Innovative processes capable of treating these would be flexible and capable of handling different types of waste streams that could consist of different steps, such as:

- Dewatering wet waste streams by extrusion and by mixing sludges with other dry waste such as: Coarse dust from silicon and ferrosilicon production, which contain quartz and coke particles (also commonly called radiclone dust); Quartz fines from mining and silicon industry. This technology could also be applied to oily mill sludges from the steel industry.
- Flotation;

- Agglomeration, through palletisation, extrusion or briquetting, to make finely granulated solid materials suitable for pyrometallurgical treatments;
- Pyro- and hydro-metallurgical treatments.

*Composites*

- (Glass-fibre) Composites can be recycled by using them in the cement sector, but trace components (like boron – which delays the settling of concrete) hinder such applications.

*Phosphorus*

Technologies of P-recovery from wet sewage sludge and sewage sludge ash are currently at TRL 6 but rather fragmented across countries due to wide differences in waste regulatory measures and actions. Demonstration activities for homogeneous market uptake and recovery plants distributed in all countries need to be considered to reach higher TRL (8-9) by 2030.

**Digital solutions to enhance processing of secondary raw materials** with advanced process control systems based on smart sensors and predictive process models that compensate for raw materials and energy fluctuations in real time, advanced analytics to identify root causes for operational issues and Machine Learning/Artificial intelligence to assess open loop process optimisation.

### 6.10.3.4 Investment needs

*<< to be filled in after the stakeholder consultation >>*

**Table 24: Investment needs in € million – work in progress and subject to change**[56]

| Technology: | Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total: |
|---|---|---|---|---|---|---|---|---|
| **Developing separation/ sorting technologies** | 2020-2030 | | | | | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Recycling within the same sector** | 2020-2030 | | | | | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Other recycling options** | 2020-2030 | | | | | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| **Digital solutions to** | 2020-2030 | | | | | | | |

[56] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **enhance processing of secondary raw materials** | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| | **TOTAL** | | | | | | | |
| | *% public funding* | | | | | | | |
| | ***Public funding*** | | | | | | | |

#### 6.10.3.5 Success factors

- The recycling of secondary raw materials requires a thorough evaluation and harmonisation of waste regulations in the EU;
- Consumer awareness on recycling needs to be improved. Much more efficient waste collection and sorting is also needed to promote increased percentages of secondary raw materials in products.
- Waste policies – removing barriers (for example regulation when it comes to handling waste streams) and creating incentives. Waste should for example be a resource to remove barriers. Including infrastructure for transport, especially cross-border;
- For household waste (where local authorities have an important role), MS should ideally organise separated collection scheme for packaging to facilitate sorting & recycling process. MS/local authorities should Invest in advanced sorting technologies for household waste/packaging;
- When household waste has been incinerated MS should invest in bottom ash treatment to recover metals;
- Development of the following key enablers:
    - Open Data and material exchange platforms that provide transparency on the quality of secondary raw materials;
    - Societal acceptance: Consumers need to value products made with recycled materials as they do with the ones manufactures with virgin materials;
    - A good exchange between the actors in the value chain.

### 6.10.4 Breakthrough process design for improved energy and resource efficiency

#### 6.10.4.1 Innovation objectives

- **Develop and deploy process intensification** solutions; the smaller equipment facilitates better process control and selectivity and lower investments and reduces energy- and feedstock-use. There is a large bulk of process intensification solutions at varies TRL levels, but deployment has been slow. With the boundary conditions changing (the increasing importance of reducing GHG emissions and energy and resource efficiency) and new enablers (digitalisation and 3-D printing) the moment to further develop and deploy process intensification solutions is now.
    - This innovation objective includes the development of **3-D printed process equipment** that reduce equipment size and improve mass- and energy-transfer and thus reactivity and product/by-product quality;
    - This innovation objective also includes **coupling of reduction and oxidation processes** in electrochemical reactions, where in the electrolysis to produce hydrogen typically oxygen can be produced as well – which is normally produced using around 200 kWh electricity/tonne of oxygen (Alavandi, 2018);

- This innovation objective also includes other disruptive energy- and resource-efficiency improvements involving hybrid or coupled processes, such as integrated reaction and separation, reactive extrusion and microfluidic reactors;

- **Develop processes that minimise non-recyclable waste:** No process is 100 % efficient, but improved process control is needed to ensure that the **outputs from each and every processes are as pure or as recyclable as possible**. The greater the purity or the greater the control over the **composition** of the by-products, the easier it will be to develop processes that are able to use those by-products and reduce landfilled or otherwise unusable materials. Aspects of this innovation objective include the following:
  - Processes the allow **recycling of out-of-spec products;**
  - Processes that are flexible to varying quality secondary raw materials and provide "up-concentrated" products of consistent quality and composition. Flexible hydro and ionometallurgical processes are examples;
- **Development of modular process solutions:** To enable resource efficiency and Hubs4Circularity, some of the processes will need to be executed at smaller scale than currently usual, and thus smaller scale, modular plants need to be developed. For example:
  - To avoid transporting huge amounts of low density waste, one would convert the waste into pyrolysis oil in small localised units, which can then be transported to larger scale operations for further processing;
  - To avoid transporting huge amounts of low energy density biomass, one would locally convert the small amounts of locally available biomass into bio-gas, which can then be fed into the gas network – thus eliminating the need to transport biomass over significant distances);
  - The trend towards **decentralised and tailor-made products** can lead to a demand for modular process solutions too.
  - The decentralised production of renewable energies will also lead to instances where the energy must be used "on-the-spot," requiring modular production facilities for chemicals and materials.

#### 6.10.4.2 Impacts

***GHG emissions:***

| **Sector** | **Current Emissions in EU,** MtCO2e | **Emissions reduction by process intensification[57], %** | **Emission reduction by reduction of non-recyclable waste, %** | **Emission reduction impact,** MtCO2e |
|---|---|---|---|---|
| Cement | | <5% | 2% | |
| Steel | | 15% | 2% | |
| Chemicals | | 20% | 2% | |
| Ceramics | | Not known | 2% | |
| Non-ferrous metals | | Not known | 2% | |
| Minerals | | Not known | 2% | |
| Water | | NA | NA | NA |
| **Total SPIRE-CCNI** | | | | |

Modular plants do directly not lead to GHG emission reductions, but energy can be saved through the avoidance of low density waste transportation and the more efficient utilisation of renewable energies. These plants will enable Hubs4Circularity and many of the recycling/use of

[57] Includes other disruptive other energy efficiency options.

secondary material options mentioned in the other innovation programmes. The goal is to have smaller, modular plants which are as efficient as the larger, established ones.

***Waste:***

| Sector | Current waste in EU, Mt | Emissions reduction by process intensification[58], % | Emission reduction by reduction of non-recyclable waste, % | Waste reduction impact, Mt |
|---|---|---|---|---|
| Cement | | Not known | 5% | |
| Steel | | Perhaps 10% | 5% | |
| Chemicals | | Perhaps 10% | 5% | |
| Ceramics | | | 5% | |
| Non-ferrous metals | | ? | 5% | |
| Minrals | | 10% | 5% | |
| Water | | NA | NA | NA |
| **Total SPIRE-CCNI** | | | | |

Modular plants do not lead to a waste reduction but enable H4C and many of the recycling/use of secondary material options mentioned in the other innovation programmes.

***Competitiveness***

Process intensification: Positive, especially for greenfield investments, due to the increased energy- and resource-efficiency and the lower CAPEX

### 6.10.4.3 Programming

- **Process intensification**:
  - For 3-D printed process equipment (currently at TRL 3), challenges are:
    - Programming is complicated (there is a need to develop computational strategies to optimise reactor shapes; this could be tackled in a CSA in 2021; 1-2 Meuro)
    - The resources one can 3D print with are limited
    - New 3D printing technologies required, aiming at increasing the printing speed and decreasing the material (metal powder) use/cost
    - 3D-printed reactors are commercially available already at small scale, but scaling up is non-trivial and there are a host of unaddressed technological safety issues such as reactant flow and heat management upon scaling up
  - Coupling of processing steps, such as reaction and separation or pre-purification and reaction, as supported by LCA of the new process vs. state-of-the-art.
  - New processes integrating multiple reaction steps in a single reactor, for example coupling secondary reactions with equilibrium-limited reactions (utilisation of Le Chatelier's principle) to increase reactant conversion, increase product yields, and decrease reactant recycling.
- **Develop processes that minimise non-recyclable waste:**
  - Failed production processes that lead to out-of-spec materials represent an avoidable waste in the process industry. Furthermore, processes can be better optimised to provide even tighter product and by-product specifications. Much of

[58] Includes other disruptive other energy efficiency options.

the technological innovation to minimise non-recyclable waste will result from advances in digitalisation. Specific goals include the following:
    - Development of processes that adjust in real time to changes in feedstock and energy inputs, without affecting the quality of the final product
    - Tighter processing controls the minimise out-of-spec materials and more stringent product and by-product specifications.
    - New process designs that allow reintegration of out-of-spec materials directly back into the process
- **Development of modular process solutions:** Despite recent progress, the application of modular processes still has technical hurdles. Specific technical challenges include the following:
  - Completion of the modular automation technology like diagnosis, maintenance and safety that is crucial for a successful application in production environment;
  - Development of new intelligent equipment designs and standards;
- **Innovation needs:**
  - Equipment for Modular Production;
    - Improved flexibility of equipment (e.g. for a broad applicability and parameter range
    - Intelligent equipment/module (e.g., self-x functionality, Integrated Sensors for Improved Process Information, link to external data for optimisation, …)
    - Miniaturisation & cost reduction of equipment (especially sensor technology, automation, process control, switch cabinets, …)
    - Smart Equipment in Intensified Up- and Downstream Processing with Additional Control Opportunities; Small & Smart Laboratory Equipment for Measuring & Optimising Intensified Process Steps
  - Operation of Modular Plants ("Plug & Produce"):
    - Remote-operation (safety & authority engineering aspects)
    - Modular Automation in continuous operation as well as process orchestration layer
    - Expand to new process areas (e.g., decentralised biorefineries, …)
    - New Business concepts (e.g., life cycle management, rental, maintenance, …)
  - Methods and Tools:
    - Life Cycle Analysis for modular plant concepts and their operating models (e.g. rental of modules, shared use, shared maintenance, …)
    - (Easy to use) Economical analysis tools to quantify the flexibility of modular plants as well as the benefit of a split in investments
    - Modelling of PEAs and the full modular plant --> digital twin
    - Modelling of Process Steps and application of Advanced Process Control for Online Optimisation
  - Standardisation:
    - Standardisation (on European level) of modular process equipment assemblies, concepts for Scale-up and Scale-up stages
    - Accelerated authority approval for modular flexible plants
    - Internationalisation of the topic (joint development, standards, …)

#### 6.10.4.4 Investment needs

**Table 25: Investment needs in € million – work in progress and subject to change[59]**

| Technology: | Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total: |
|---|---|---|---|---|---|---|---|---|
| **Developing and deploy process intensification** | 2020-2030 | | 50x €3 | | | €1.5 | | |
| | 2030-2040 | | 50x €3 | 20x €13 | | | | |
| | 2040-2050 | | 50x €3 | 20x €13 | 10x €25 | | | |
| | ***Total*** | | | | | | | |
| **Develop processes that minimise non-recyclable waste** *<< numbers uncertain >>* | 2020-2030 | | 15x €3 | | | | | |
| | 2030-2040 | | | 6x €13 | | | | |
| | 2040-2050 | | | | 3x €25 | | | |
| | ***Total*** | | | | | | | |
| **Development of modular process solutions** | 2020-2030 | | 10x €3 | 4x €4 | 2x €4 | | | |
| | 2030-2040 | | | | | | | |
| | 2040-2050 | | | | | | | |
| | ***Total*** | | | | | | | |
| | **TOTAL** | €0 | €525 | €614 | €333 | €2 | €0 | €1,474 |
| | *% public funding* | | | | | | | |
| | ***Public funding*** | | | | | | | |



#### 6.10.4.5 Success factors

- Digitalisation
- General development of 3D printing and its capacity, and establishing norms, standards and safety regulations for 3D printed reactors
- The adjustment of international legislation procedures and rules to the new flexible concept of modular solutions is necessary

[59] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## 6.11 Minimising the environmental footprint of materials

### 6.11.1 Innovative materials from Process Industries

#### 6.11.1.1 Innovation objectives

The overarching objective is to develop **new processes and materials that simultaneously optimise technical and the ecological performance over their full life cycle.** This objective is broken down into the following innovation objectives, specifically:

- **New materials responsive to mechanical, thermal or electromagnetic stimuli**, which could be applied in separation technologies;
- ***In situ* functionalisation and defunctionalisation of materials** (e.g., self-healing cement).

#### 6.11.1.2 Impacts

The key GHG emission reduction and resource efficiency impacts of this innovation programme are in other, non-process industry sectors or indirect, as the materials might reduce the demand for the materials from the process industry (for example in the case where self-healing reduces the replacement rate thus reduces the challenge of the process industry's transition).

By increasing the added value per product, the European process industry's competitiveness is (potentially) increased.

#### 6.11.1.3 Programming

The process industry is constantly improving its materials. Cross-sectorial material development should provide better, more sustainable solutions.

This innovation programme aims to stimulate accelerated development of materials meeting the innovation objectives, as these reduce the challenge of the its transition and the societies transition (eliminate GHG emissions and resource efficiency).

#### 6.11.1.4 Investment needs

**Table 26: Investment needs in € million – work in progress and subject to change[60]**

| Timing[61] | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| 2020-2030 | | 50x €3 | 20x €5 | 10x €10 | | | |
| 2030-2040 | | 50x €3 | 20x €5 | 10x €10 | | | |
| 2040-2050 | | 50x €3 | 20x €5 | 10x €10 | | | |
| **Total** | €0 | €450 | €300 | €300 | €0 | €0 | €1,050 |
| *% public funding* | | | | | | | |
| ***Public funding*** | | | | | | | |

#### 6.11.1.5 Success factors

- LCA guidelines for the validation of minimised environmental impact (GHG emissions and pollution reduction) for the combined production and lifetime of materials/products, as compared to state-of-the-art;



[60] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.
[61] These numbers only include programmes dominated by environmental performance, and assuming companies' appetite for involving public funding for their product development.

### 6.11.2 Inherent recyclability of materials

#### 6.11.2.1 Innovation objectives

The complexity of sophisticated products makes the recovery of secondary raw resources of appropriate quality for reuse difficult and materials produced by the process industries are not designed to be reused or recycled. Material design is paramount for both "Design for Recycling" and "Design from Recycling." Recycling applicability is often hindered not just by the heterogeneity of the waste streams, but by product-parts being a mixture of several materials, such as in the case of multi-layers and composites. There is a case to be made to change the designs in such a manner that more/only recyclable materials are used. However, ultimately the full life cycle impact counts, and in some/many cases complex materials will/can be incinerated at the end of their life, might lead to lower GHG emissions then simpler materials that can be recycled many times at the expense of higher material use/emissions during use. This innovation programme aims to achieve a shift enable the manufacturing industry to make more recyclable products, via:

- **Replacement of multiple component materials (such as mixed plastic composites and hybrids) that are difficult or impossible to recycle with a single, recyclable material or a material that is easily separable into constituent, recyclable materials,** including new materials that are not available yet. Functionality in many of today's products are created from the combination of multiple materials. While the combination provides the desired properties, the asymmetry in the type of materials – different polymers or polymers and other materials like steel or concrete – make recycling of these materials very difficult or impossible. Advances are needed that can replace these multicomponent, inherently difficult-to-recycle materials by single materials or a suite of materials that are more compatible to recycling;
- **Develop tracking/tracing systems** as enabler to determine the quality, bio-based/recycled content and the $CO_2$ footprint of secondary raw materials.

#### 6.11.2.2 Impacts

**GHG emissions:** The recycling processes should be operated on “no greenhouse gas emitting energy”, and their energy use should be optimised.

**Waste:** The resource efficiency will increase as a consequence of this innovation programme, and the amount of landfilled materials would decrease.

**Competitiveness:** The competitiveness of the process industry increases when the resource efficiency increases while maintaining its functionality.

#### 6.11.2.3 Programming

- **New better materials to replace non-recyclable (composite/hybrid/multilayer) materials**: Development of these processes is still at the start but is expected to continue over time.

- **Develop recycling processes for composites/hybrid/multilayer materials):** Development of these processes is still at the start.
- **Use of tracking/tracing systems** (included in the above).

#### 6.11.2.4 Investment needs

**Table 27: Investment needs in € million – work in progress and subject to change**[62]

| Technology: | Timing | TRL 1-3 | 4-6 | 7-8 | **9** | Non-technological | Deployment | Total: |
|---|---|---|---|---|---|---|---|---|

[62] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **New better materials to replace non-recyclable (composite/hybrid/ multilayer) materials** | 2020-2030 | | 50x €3 | | | | | |
| | 2030-2040 | | 50x €3 | 20x €5 | | | | |
| | 2040-2050 | | 50x €3 | 20x €5 | 10x €10 | | | |
| | ***Total*** | | | | | | | |
| **Develop recycling processes for composites/hybrid/ multilayer materials)** | 2020-2030 | | 50x €3 | | | | | |
| | 2030-2040 | | | 20x €13 | | | | |
| | 2040-2050 | | | | 10x €25 | | | |
| | ***Total*** | | | | | | | |
| | **TOTAL** | €0 | €600 | €810 | €350 | €0 | €0 | €1,410 |
| | *% public funding* | | | | | | | |
| | ***Public funding*** | | | | | | | |

### 6.11.2.5 Success factors

- Blockchain technologies to track and trace component parts, specifically for their composition for eventual inclusion as secondary raw materials in the same or different process.





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## 6.12 Process technologies for industrial-urban symbiosis

### 6.12.1 Demonstration of industrial-urban symbiosis

#### 6.12.1.1 Innovation objectives

The goal of this innovation programme is to realise demonstration projects for Industrial Urban Symbiosis (IUS). This means that projects should be developed that identify, combine and integrate multiple technologies and/or business models to demonstrate IUS.

These demonstration projects can be using existing technologies or new technologies. If existing technologies alone are used, the funding from this innovation programme will be the only funding. However, if the project demonstrates not only IUS, but also new technologies from any of the other innovation programmes, these technologies can be funded from that innovation programme. That can be for example the digital technologies to track material flows and ensure that waste

The IUS demonstration projects can be focused on water, energy, and/or materials (both urban and industrial flows).

#### 6.12.1.2 Impacts

*<<This will be based on the still unpublished report Study and Portfolio Review of Cluster of Projects on Industrial Symbiosis in Directorate Prosperity (former Industrial Technologies) in DG R&I: Findings and Recommendations by Klaus Sommer. The results will be included here after publication.>>*

#### 6.12.1.3 Programming

IUS needs to be demonstrated in various applications and regions. Therefore 3-5 projects should be funded per year. After 2024 the innovation programme will be evaluated, and a decision will be made on how many calls are needed still before the market picks it up – also in the context of the SPIRE-CCNI project portfolio and necessary priorities. After 2024 the number of projects per year can increase or decrease as a result.

#### 6.12.1.4 Investment needs

Project costs can be in the range of €10-€25 million, so taking the average of that range (€17.5 million) times on average four projects per year = €70 million per year. For 3 years that amounts to €210 million until 2024. For the investment estimate we assume that the annual funding remains constant post-2024. We assume that by 2030 enough demonstration projects have been done to allow the market to pick up the further roll out.

**Table 28: Investment needs in € million – work in progress and subject to change**[63]

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| **2020-2030** | | | 36x €17.5 | | | | €630 |
| **2030-2040** | | | | | | | |
| **2040-2050** | | | | | | | |
| **Total** | €0 | €0 | €630 | €0 | €0 | €0 | €630 |
| ***% public funding*** | | | | | | | |
| ***Public funding*** | | | | | | | |

[63] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

#### 6.12.1.5 Success factors

- Waste policies – removing barriers (for example regulation when it comes to handling waste streams) and creating incentives. Waste should for example be a resource to remove barriers. Including infrastructure for transport, especially cross-border.
- MSW collection is a prerequisite for the availability of waste streams. Not only should enough volume be available, but also adequate separation and sorting is needed to deliver the right quality of the streams
- Technologies from other IPs – many technologies can be used in IUS. Sometimes proven technologies can be used, but in other cases new technologies are needed. This can be for example CO2 capture technology (innovation programme 6.7.1 Flexible $CO_2$ capture and purification technologies), membranes for separation (innovation programme 6.5.2 Electrically-driven separation), or digital technologies that enable tracking of material flows (innovation programme 6.17.2 Towards fully connected process industries – scheduling across plant networks/sites/industries/municipalities - industrial symbiosis).
- Legal possibility to do it and framework for negotiation of contracts – policies and regulations can in cases act as a barrier for implementation of IUS projects. These barriers should be removed on a European, member state, and local level.
- Facilitating role – to bring different parties together to explore IUS opportunities, a facilitator has proven effective (as confirmed by report Klaus Sommer). This can be provided by the hubs for circularity and/or community of practice (see innovation programmes 6.13.3 Development of Hubs of Circularity and 6.13.2 Community of Practice)

## 6.13 Business models and demonstration of I-US

To stimulate the development and implementation of business cases and demonstration of IUS an approach is required that meets the needs on two levels:

- **On the regional level** there is a need for a facilitator to map the local needs, opportunities and stakeholders.
- **On the European level** there is a need for a “Handbook for IUS” that captures all the best practices, guidance, frameworks, tools and technological know-how from European regions

To meet these needs an approach is designed where on the local level Hubs for Circularity (H4C) are created, and on the European level, Community of Practice emerge that are strongly linked to the H4C as a network of networks.

### 6.13.1 Impacts

***GHG emissions***

*<<This will be based on the still unpublished report Study and Portfolio Review of Cluster of Projects on Industrial Symbiosis in Directorate Prosperity (former Industrial Technologies) in DG R&I: Findings and Recommendations by Klaus Sommer. The results will be included here after publication.>>*

***Waste***

*<<This will be based on the still unpublished report Study and Portfolio Review of Cluster of Projects on Industrial Symbiosis in Directorate Prosperity (former Industrial Technologies) in DG R&I: Findings and Recommendations by Klaus Sommer. The results will be included here after publication.>>*

***Competitiveness***

*<<This will be based on the still unpublished report Study and Portfolio Review of Cluster of Projects on Industrial Symbiosis in Directorate Prosperity (former Industrial Technologies) in DG R&I: Findings and Recommendations by Klaus Sommer. The results will be included here after publication.>>*



### 6.13.2 Community of Practice

#### 6.13.2.1 Innovation objectives

Even if the implementation of industrial-urban symbiosis and closing circularity loops are still in their infancy, they are by far not new concepts. Many initiatives and publicly funded projects have been running on various levels, European, national, regional. Many interesting tools, models and technologies have been developed, which, however, are insufficiently visible or accessible for managers of symbiosis. The full understanding of their practical value for specific cases is missing, as well as the clarity about the existing gaps. The projects disseminate their results individually during their life time, but this usually takes place in individual events with limited audience participating, and the measures extinguish gradually with the time after funding.

There is a need of evaluation, systematic representation, constant update and provision of symbiosis and circularity related solutions. The aim of this programme is to:

1. Build Community of Practice (overarching H4C)
2. Enable prioritisation of IUS projects
3. Collecting knowledge and tools, etc., and making this accessible
4. Synthesise findings into generic learning/frameworks, etc., and keep knowledge about state-of-the-art solutions up to date
5. Train circular practitioners that can drive H4C roll-out across Europe

#### 6.13.2.2 Impacts

This is discussed at the level of the innovation area

#### 6.13.2.3 Programming

A research programme is foreseen with the following actions addressing the objectives:

**Build Community of Practice (overarching H4C) and Synthesise findings into generic learning/frameworks etc. and keep knowledge about state-of-the-art solutions up to date**

The aim of the Community of Practice will be to:

- Collect knowledge, learnings, and best practices, as well as tools and data
- Synthesise generic frameworks and tools for IUS from this information
- Keep the information and tools up to date
- Proactively connect to Hubs4Circularity to deliver relevant information to them and collect information on for example challenges and best practices
- Train circular practitioners that can roll out the H4C concept across Europe

The initial collection of information will be dealt with in the other actions in this programme.

The collected information will be managed by a small team of people with sufficient technical expertise and various backgrounds in terms of industries and regions, that can build, maintain and manage the network, initiatives, and knowledge base. This can be done as well in partnership with other initiatives with similar needs. Costs for this team are estimated at €0.5 million annually.

The Community of Practice will develop general cross-sector symbiosis evaluation tools and governance models for the operation of a H4C. This will include issues such as anti-trust limitations, transparency, mutual long-term dependencies as well as the proper calculation and redistribution of gains between symbiosis partners. Governance models could include the coordination of municipalities planning with industrial activities, i.e. for the development of infrastructure for secondary flows exchange and transport and co-location for green field eco-parks, water related infrastructure, or energy infrastructure. They will comprise business-to-territory models for the provision and operation of connecting infrastructures, for the logistics of the material flows for recycling – tracking, collection, transport, for shared procurement and services, such as maintenance, security, training, etc.

The Community of Practice will engage with other stakeholders (e.g. local universities or other education institutions) to facilitate the training of circular practitioners. These practitioners should have an in-depth understanding of industrial and urban symbiosis, the state-of-the-art tools and databases, and newest business models. Based on this knowledge base, the circular practitioners will be able to spread the H4C concept to all regions of Europe.

To keep the information up to date the Community of Practice will connect to the existing activities on circularity as well as all running relevant projects from other innovation programmes to evaluate and include the results into their database and tools and frameworks. The funded projects under SPIRE-CCNI will be required to collaborate in providing the information.

In the interaction with the H4C, the Community of Practice need to track the needs of regions with regards to IUS so they can tailor the information to cater the needs. H4C are required to rate the services of the Community of Practice to assess whether the services are useful (rating system). If useful, the Community of Practice will also connect similar H4Cs to enhance sharing of best practices ("twin hubs"). Potentially an IT living platform could be beneficial, preferably based on the platforms designed in projects so far. This will aggregate the above data and make it accessible for the H4C. This will allow for constant updating with further developments. Such a platform should build upon or incorporate the already existing ones, resulting from past or running projects. Costs are estimated at €1 million.

The functions of the community of practice should be evaluated. In this evaluation the business value generated by the community of practice should be considered, and a decision should be made in 2024 whether the approach should be changed or not. The evaluation is estimated to cost €0.5 million.

**Enable prioritisation of IUS projects**

The European industry and municipalities will first be systematically screened for major material flows with potential of entering symbiosis, mapped, and evaluated on expected impact as well as boundary conditions for the implementation of symbiosis (such as the need for new infrastructures or change of regulations). This should build on, and especially bring together, the available public data (for example the E-PRTR database, country databases, permit registries, and data from existing initiatives). A framework should be developed for prioritisation of flows and identifying geographical sweet spots for IUS. Costs are estimated to be €2 million for a 3-year project.

The functioning of the framework should be evaluated in 2024 and updated accordingly. This needs to be done by an independent party, involving a panel of various stakeholders. Costs are estimated to be €0.5 million.

**Collecting knowledge and tools etc. and making this accessible**

All project results should be screened for relevant technologies, business models, IT platforms, decision-support tools and possible organisational, legal and societal change concepts, evaluate them according to applicability for specific implementation cases and indicate gaps and weaknesses. This work should build on the report by Klaus Sommer[64] and provide more detail. Detail is needed on how the used technologies can be used elsewhere, what are the bottlenecks and limitations, including a critical and practical evaluation. Costs are estimated to be €1 million.

#### 6.13.2.4 Investment needs

For the investment needs we assumed that the evaluation in 2024 is positive. The team is expected to grow over time as more H4C emerge, and then shrink post-2040.

**Table 29: Investment needs in € million – work in progress and subject to change[65]**

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| **2020-2030** | Technology investments included in the other innovation programs | | | | €7 + €2.5 + €1 | | €10.5 |
| **2030-2040** | | | | | €10 | | €10 |
| **2040-2050** | | | | | €6 | | €6 |
| **Total** | €0 | €0 | €0 | €0 | €27 | €0 | €27 |
| ***% public funding*** | | | | | | | |
| ***Public funding*** | | | | | | | |

#### 6.13.2.5 Success factors

- Hubs for circularity sharing experience learnings and knowledge with the community of practice
- SPIRE-CCNI projects sharing learnings and detailed project information

[64] This evaluation should build on the findings from the report by Klaus Sommer (contracted by DG R&I) that will be officially presented for discussion on November 4th, 2019, in Brussels.
[65] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

### 6.13.3 Development of Hubs of Circularity

#### 6.13.3.1 Innovation objectives

This programme is about enhancing and facilitating the practical implementation of industrial-urban symbiosis and circularity in regions, embracing clusters of process industry and municipal infrastructures (including energy infrastructure), and thus unlocking the market potential of relevant technologies and solutions at hand for increased resource efficiency, decreased pollution and GHG emissions, and decreased consumption of fossil-based materials.

The concept of industrial symbiosis has already been investigated in many ways, technologies are still being developed (mostly also in parallel Innovation Programmes within this SPIRE-CCNI roadmap). Nevertheless, even if existing technology gaps are planned to be closed in short or mid-term, still severe non-technological barriers will hinder implementation if left unchanged. The Readiness Level of industrial-urban symbiosis needs to be measured not only in terms of technology, but also in terms of the managerial and social and economic readiness for implementation. A holistic approach is necessary.

The conditions in regions vary, depending on the presence of specific industries and stakeholders, the corresponding availability of current and future material flows, the (un)availability of infrastructures, specific legal or financial constraints related to them. Each implementation will therefore face own specificity. Some of the challenges are of universal character and can be tackled on the European level, whereas many of them are region and case related and can only be successfully dealt with when approached individually within a region, addressing the specific needs and engaging with regional stakeholders.

The results of SPIRE-CCNI projects related to industrial symbiosis and of discussions with pioneering symbiosis regions (e.g. Kalundborg, Smart Delta Resources, trilateral region of North Rhine Westphalia (DE), Flanders (BE) and the Netherlands, Mo Industrial Park or South Norway Cluster), imply that bridging the Valley of Death for industrial-urban symbiosis requires the development of brokerage tools and support mechanisms in the industrial parks or regions that could enable working across the limits of individual companies, embracing whole value chains across sectors. This is where Hubs4Circularity enter the stage.

The objective of this innovation programme is to contribute to the realisation of industrial-urban symbiosis and GHG emissions reductions by supporting the development of Hubs4Circularity. The needs likely differ for different regions. The form and intensity of required support depends among others on the existing regional structures:

- Hub 4 circularity setup from scratch can be necessary for regions where no structures exist yet. Then it might for example require a small dedicated team of 2-3 people to coordinate between stakeholders and assess IUS opportunities. Emerging hubs can be connected to similar H4Cs (twin hubs).
- If there are already collaborative stakeholders, the support can be an add-on. For example, an additional team member in existing team to connect and align with the community of practice and using the learnings and identify opportunities from the community of practice and help implement the IUS in the H4C.

Besides the existing structures the H4C also will connect to emerging structures where relevant. This can be for example territory hydrogen sites for hydrogen or Living Labs for water.

Here is a list of possible actions that could stimulate the development of Hubs for Circularity:

- Establishment of management and brokerage structures or development of existing structures to incubate the Hub for Circularity. The nature of such structures needs to be individual – best addressing the needs and peculiarity of the regions.
- Specification of generic and region-specific non-technological (crossborder, international) barriers to implementation (policies, stakeholders and their interests)

- Mitigation of these barriers: the options and their prospects, acceptance finding, implementation plans and execution trajectories, cross-border synchronisation
- Connecting local stakeholders (process industries, other sectors, public sector, civil society and finance) within the regions and across regions
- Analyse the specific material flows, strengths and weaknesses, develop business cases and models for their use for symbiosis and advocate for the application with the relevant regional stakeholders
- Based on the analysis mentioned above, the development of a regional business strategy towards symbiosis and circularity, incl. the CO2 abatement and climate neutrality goals.
- CCU can create new industrial hubs in the future, where standalone plants can be the feedstock for new industries in the future and can also provide heat.
- Depending on the potential implementation cases, use of available tools and development of collaboration projects addressing closing the gaps for symbiosis launch, both focused on the technologies and on dealing with non-technological barriers aiming at de-risking the investments
- Finding and activating financial means for the implementation, comprising complementary funding instruments on all levels
- Extensive collaboration with the industries to foster the implementation of cases and demonstration projects
- Networking with EU- wide community of practice to exchange best practices
- Disseminating the knowledge on the symbiosis and business opportunities to share knowledge and to attract the interest of stakeholders to get involved in the region wherever of advantage.

Based on the analysis of the regional potential and of arising new value chains, it can be found out that companies of a specific kind are missing in the region to close loops and that specific factors impede the establishment of such companies.

The programme will therefore also include measures to attract new companies (services or production sites) to regions to establish or complement new value chains. Such companies could be potential takers of material or side flow takers or solution providers for symbiosis or circularity sites. Here a high potential for start-up and SMEs is seen.

The support is expected to cost on average €0.5 million per year per H4C. Each H4C should develop its own business-to-territory plan and co-investment model to be funded by the region itself. This is expected to take up to 3 years. Therefore, costs are estimated to be up to €1.5 million per H4C.

#### 6.13.3.2 Impacts

This is discussed at the level of the innovation area.

#### 6.13.3.3 Programming

**A research programme** is foreseen with:

- **Until 2030**: To deliver the 15 lighthouse H4Cs in 2030, up to 20 Hubs4Circularity are to be funded in Europe (to account for the risk that some H4Cs might not develop as fast as others);
- **2030-2040**: Development of at least 20 Hubs4Circularity in Europe;
- **2040-2050**: Development of at least 10 Hubs4Circularity in Europe;

The incubation/development of Hubs is suggested to be supported with an EC contribution of up to €1 million each over the time of 2 years each. The use of the funds will be according to the individual B2T plan and co-investment plan; can be for personnel costs and/or for any knowledge-intensive or data-intensive services, whatever appears most necessary or suitable to attain justified impactful results in the specific region and to create transferrable knowledge. The necessary pre-condition for the implementation should be:

- Support and commitment of stakeholders in the regions (only one Hub in the regions for an area – no doubling or overlaps). Such support will manifest itself in combined financing schemes for the Hubs, with contribution from the industry and from regional authorities.
- Business Plan for the sustainability of the Hub in the region – how will the Hub secure own existence and financing after the period of public funding to continue to find opportunities for symbiosis and GHG emissions reductions.
- Co-investment framework including funding by the regional authorities or other needed instruments (e.g. infrastructure and industrial infrastructure funding) and industrial or other private investments

The H4C will have regular interaction with the Community of Practice to share learnings, best practices, tools and frameworks, but also to receive guidance form the Community of Practice.

#### 6.13.3.4 Investment needs

Assuming that a H4C team costs about €5 million per decade, the remainder is deployment costs. Note that this does not include the funding for innovative projects. These are funded from the other innovation programmes.

**Table 30: Investment needs in € million – work in progress and subject to change[66]**

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological | Deployment | Total |
|---|---|---|---|---|---|---|---|
| 2020-2030 | Technology investments included in the other innovation programs | | | | 20x €1.5 | 15x €3.5 | |
| 2030-2040 | | | | | 25x €1.5 | 20x €3.5 + 15x €5 | |
| 2040-2050 | | | | | 17x €1.5 | 15x €3.5 + 35x €5 | |
| **Total** | €0 | €0 | €0 | | €86 | €425 | €511 |
| *% public funding* | | | | | | | |
| ***Public funding*** | | | | | | | |

#### 6.13.3.5 Success factors

- Community of practice sharing best practices
- Local/regional support from industries, other sectors and local authorities. The local actors should be well-informed about the potential value of H4C.
- Other innovation programmes happening in the hubs



[66] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## 6.14 Introduction to digitalisation in the process industry

### 6.14.1 Introduction

The Innovation Areas covering digilisation are structured as following:

**1. Digitalisation of the design phase of processes and materials**. Through data and information sharing within and across value chains, with customers and within the R&D-ecosystem topics like recyclability of end-of-life products can be integrated in the early design phase of materials and the processes to make these materials. Furthermore, advanced modelling and applying 'Digital Twins' and other digital solutions to design materials and processes can speed up the design phase, shorten time-to-market and result in processes with higher energy and resource efficiency, and contribute to flexibility and enhanced safety of operations.

**2. Digitalisation of plants**. Digital technologies such as advanced sensors, model predictive control, and real-time optimisation are needed to operate in a flexible and agile manner but nonetheless higher efficiency and reliability. Reliable predictions of remaining lifetime and predictive maintenance will significantly reduce unplanned shutdowns and lead to improved efficiency.

**3. Digitalisation of connected processes and supply chains**. Digital technologies can help to improve the management of highly connected processes to ensure efficient use of production assets, resources and energy while safeguarding quality, yield and reliability. Supply chain digitalisation will happen within a company or production chain, integrated with the upstream and downstream value chains, and across industries and within regions and municipalities (urban-industrial symbiosis).

The sections below outline the Innovation Areas SPIRE-CCNI will focus on to drive the European Process Industries towards a new, digitised way of operating.

The programming of the innovation programmes is up to 2030. Given the speed of innovation of digital technologies, the programme focuses on a 2030 timeline, the horizon beyond can be added in the foreseen regular updating of this Roadmap, following new insights on the fast-evolving digital technologies that will be available by that time.

### 6.14.2 Impact on GHG emissions and waste

Digital technologies will enable reduction of emissions through increase in yield and efficiency improvements both in the process industry itself and across value chains. In many cases digital technologies will be an essential and integral part of other innovations in the process industry, e.g. through real-time information flows to support industrial-urban symbiosis, increasing the potential of power demand response and flexibility, providing digital material passports or distributed ledger technologies that enhance the recyclability of materials. Since digital technologies are part of the solution, it is not possible to isolate the impact on GHG emissions or waste reduction.

Digital technologies can also directly increase the efficiency of current processes. The impact depends heavily on the process and the digital technologies applied. A study to the application of Artificial Intelligence to a cement kiln showed that an 11.6% efficiency gain could be achieved (McKinsey, 2019). Another study to the digital opportunities in the metals industry concluded that through yield, energy and throughput analytics and improvement of EBITDA of 2-3 % could be achieved (McKinsey&Company, 2018). Yet another study showed that in the chemical industry the potential for increasing efficiency through digital processes varies from 5-40%, depending on the specific chemical industry and the step in the value chain (VCI/Deloitte, 2017), see Figure 20. Obviously, these studies cannot be compared to each other as scope and definitions of efficiency are quite different.

In 2015 the World Economic Forum has launched the Digital Transformation of Industries (DTI) initiative, with a key focus on quantification of the value at stake for both business and society. In one of the white papers, an assessment is made of the impact of digital technologies on $CO_2$-emissions and workforce (World Economic Forum & Accenture, 2016). Their analysis shows that digitalisation can have a positive effect on the decoupling of economic growth and growth in $CO_2$-emissions and resource intensity. The global impact as estimated at 26 billion tonnes of net avoided emissions between 2016 and 2015. Of the SPIRE-CCNI industries, only the chemical industry was examined in more detail. The estimated net emission reduction in this period is 56 million tonne of $CO_2$, further specified to 60-100 million tonne of $CO_2$ in a white paper dedicated to this sector (World Economic Forum & Accenture, 2017). This emission reduction can be achieved digitalisation of processes, for example via advanced automation and process control, predictive maintenance and real-time process, quality and emission control. These elements are covered in or innovation programme, "Digitalisation of plant and plant operation."

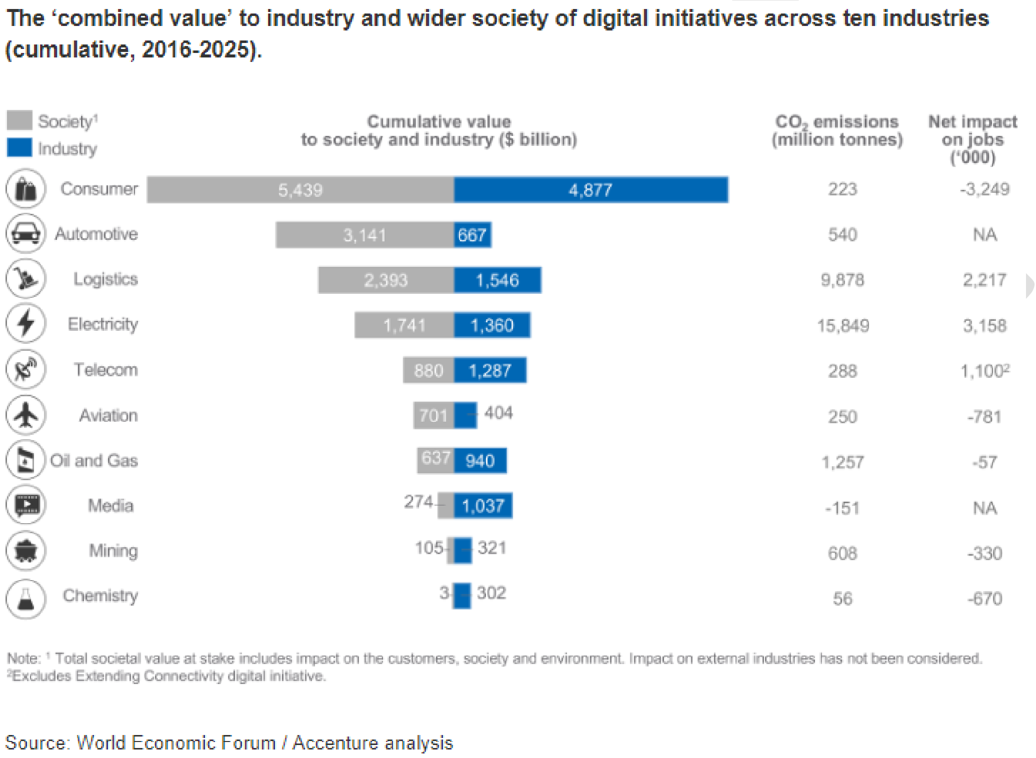


**Figure 19: Estimate of the global impact of digital initiatives on society (World Economic Forum, 2019)**

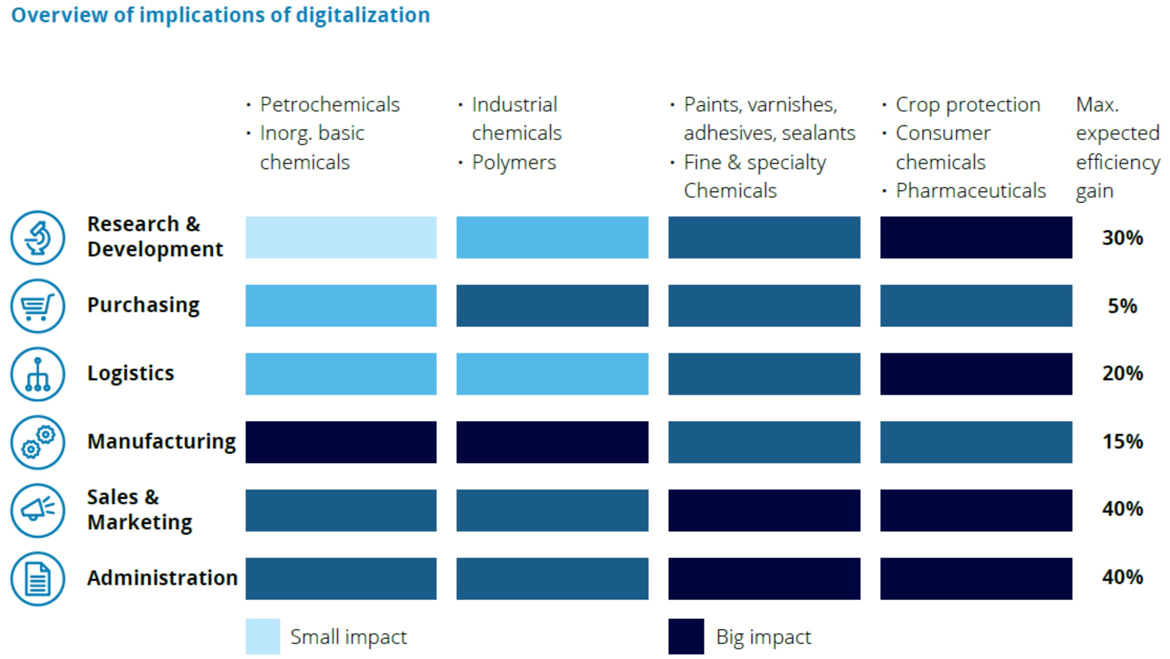


**Figure 20: Overview of implications of digitalisation in the chemical industry (VCI/Deloitte, 2017)**

### 6.14.3 Competitiveness

- Loss of opportunity
- Flexibility and yield
- Time to market shorter
- Enable new business models

### 6.14.4 Success factors

**1. Train the workforce in digital skills**

The Need: The digital transformation of the process industry will require building on competence in designing, performing and implementing digital technologies. Moreover, 'Industry 5.0' is expected to merge the high-speed accuracy of industrial automation with the cognitive, critical thinking skills of humans'. Data Science and robotic experimental platforms will become enablers alongside conventional R&D, modelling and the tools of Process Systems Engineering. Digitalisation also offers access to 'digital twins' and AI-driven simulation environments. However, to make the most of the digital revolution it will be essential to merge conventional skills and knowledge of science and engineering with the emerging capabilities of digital technologies.

State-of-the-Art: Current engineering university courses are strong on conveying the fundamentals of thermodynamics, kinetics, and transport processes. All have significant digital skills components including competence in the use of simulation tools and control theory and practice. Some have experience of programming and software management. The core Process Systems Engineering capability of optimisation, dynamics, advanced control, and supply chain analysis are covered in some Universities where there is respective expertise. In some cases, this is seen as a postgraduate expertise. There are emerging undergraduate courses and post-graduate training centres in the digital technologies underpinning the development of industry 4.0. The evolving area of data science is, currently, a specialist area in which chemists and chemical engineers are not highly involved. However, there is a rapidly developing skills base in chemistry, physics and material science with respect of informatics, data science, machine learning, robotics and AI.

Future needs- outlook: To make the best use the digital transformation for the process industries sectors, it will be increasingly important to enhance the digital skills competence of existing workforce of the industry as well as new scientists and engineers. Digital skills requirements evolve very fast, making it challenging to keep pace with.

Engineers and scientists will need to develop an appreciation of the strengths and limitations of new digital technologies in areas such as data science, machine learning, robotics and artificial intelligence and the ability to apply systems thinking. This will need to be incorporated in University training to complement systems engineering and modelling skills that are covered in modern programmes already. Graduates of these programmes are not yet 'digital natives' but well-trained in applying and critically reflecting the opportunities and limitations of the techniques. The bigger challenge is to upskill the existing workforce of scientists, engineers, process operators and managers, considering the dynamic and fast-paced evolution of digital technologies and skills requirements. This is a very significant task and requires not only education on new tools and techniques but also a change of mindset to place more trust in digital technologies while at the same time retaining a critical view of limitations.

**2. Ensure cybersecurity**

The deployment of digital technologies will increase the vulnerability to cyberattacks, which poses significant risks for plant safety and plant operations and can result in down-time of the plants and harm to employees, customers and other stakeholders. Working across value chains or within industrial-urban clusters with digital technologies will involve sharing of data with other parties, even data that are seen as confidential by the companies, accelerating the risks for data theft and/or misuse of the data. Concerns about intellectual property protection, data ownership and privacy must be tackled, and companies also often need to review internal procedures and policies to effectively collaborate in digital ecosystems.

New and improved way to manage this increasingly complex cybersecurity space is of the utmost importance for process industries to make the digital transformation successful. This development is not just one for the process industry but has to be taken forward by the whole digital community. However, in the era of data-exchange and value generated through data-ownership, the process industry is an important stakeholder in initiatives on industrial cybersecurity. Thus, the process industry might develop advanced security solutions to prevent misuses of stored data and attack of plant control and wireless systems or cloud data in an environment where data are more and more geographically dispersed from the viewpoint of remote data-serves and manufacturing hubs.

**3. Organisations must get ready**

Although digital transformation is already happening in the process industry, organising the innovations associated with digital technologies is a challenge for many process industries. Time of staff needed to deliver expertise is a limiting factor in industries where the margin is under pressure and there is not much space for other business than running the process.

The integration and interoperability of digital systems and platforms is not only a technical challenge but includes organisational alignment efforts, too, as responsibility for information technology and operational technology is often spread across multiple departments.

A digital strategy is needed at board level that sets out the transformation needed and outlines the priorities and allocated time to experts.

**4. Co-create with digital industries and other partners**

A crucial success factor for the digital transformation in the process industry is that the digital solutions are developed and suitable for application in the process industry. Co-creation of these solutions with the digital industry is crucial, as is investing time to identify needs of network partners and to understand complexities.



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## 5. The EC Digital Single Market Strategy

Building a European data economy is a key part of the European Commission's Digital Single Market strategy. EU intends to unlock the reuse potential of different types of data and its flow across borders to achieve a European Digital Single Market. Data sharing and reuse by multiple actors maximises value extraction and leads to the creation of new services and the emergence of novel business models. Data sharing often represents one of many steps of digital transformation of a company. However, the lack of operating platforms for secure and controlled sharing of "closed" datasets (proprietary/commercial/industrial data) seriously limits the capacity of Europe to respond to the digitalisation challenge of the chemical industry. The relevance and efficacy of data sharing platforms in digitising business capabilities for the process industry becomes applicable to enable connected value chains, industrial symbiosis, or technology transfer. Through 'Open Science', research communities are moving towards much more transparent environment for publishing research results, and smart access to such data will help innovation in the industry. Sharing of data along the value chains will further enhance product qualities, reduce energy usage and further improve recycling/reuse efforts of water.

## 6.15 Digitalisation of process/product R&D

Digital technologies applied within early product and process development stages in the process industries will largely **speed-up innovation**, allowing **more efficient "idea-to-market" processes**, e.g. through less-unproductive experiments by taking advantage of all previous results and company knowledge in the experimental design phase. Digitalisation will allow a quick response to market and customers' demands through **integration of customers into the R&D-processes**. Digitalisation will enable the ability to **integrate life cycle thinking and advanced sustainability assessments** towards the targeted solution.

R&D activities will be empowered through leveraging the whole sets of knowledge and data available – supported through **advanced data analytics/Artificial Intelligence** – receiving even lost or hidden knowledge and know-how. Digital technologies will help to **manage the increasing complexity of future connected industries** that is expected to even further increase if circular economy will be implemented (e.g. recycling-by-design, new variable feedstocks etc.)

Research and innovation in the fields of "process" and "product" could be seen in different ways, depending on the kind of process industry. In some industries the first step is always the development of a new product followed by the development of a suitable process or a process chain to produce this product. In other industries the kind of process or process chain is constant over long time periods and the development of new products is rather limited by the existing production plants and their capabilities. Independent of the specific situation in each process industry, it is without any doubt that **digitalisation will play an increasing role in the field of development of new products as well as in the development of new or the adaptation of existing processes**. For the development of new processes or the adaptation of existing ones the most important point is the availability of **full process simulation models/digital twin for the complete chain of production process** which consider all aspects of production. These models can afterwards be used in combination with suitable optimisation strategies to solve the problem of often contradictory demands between optimal product quality, lowest productions costs and optimal energy/resource efficiency and environmental footprint.

By the **consequent digitalisation of the product and process development process** and the suitable handling of all information and data which are produced during this process many positive effects could be reached. E.g., these data could be used to design the production processes in a much more automated and optimised way than it is realised today. Furthermore, these data built the first base of a **Digital Twin of the product**, which can be enriched in later stages by all data coming from the production processes and which will then accompany the product through its whole life cycle, e.g., more efficient recycling processes

After the processes has started to operate, online data produced during operation (process variables in combination with product quality features) could significantly help to develop better products with the final aim to realise in the future a **fully auto-adaptive process**.

### 6.15.1 Towards digitally supported design of environmentally benign high-performance materials

This programme focuses on the development of new digital technologies for supporting all development phases of innovative materials. The digital capabilities will drastically increase the efficiency of the development of tailored materials that provide the requested value to the end-users of the materials and can be produced in a sustainable fashion also from bio-based or recycled feed material and be recycled or re-introduced in the production cycles of a circular economy. A quick response to market and customers' demands will be achieved through data-sharing with customers and early integration of end-of-use handling of the products into the R&D-processes. Topics such as safe-by-design, life cycle assessment, circularity-by-design, feedstock complexity must be tackled already at the R&D design and experimentation stage and in connection with the development of the production processes. An ecosystem of digital tools and databases across complex R&D pipelines must be developed. Access to and exchange of data beyond the borders of a company will gain importance, hence a challenge is data and IP protection.

With the main goal of making R&D more efficient and effective, materials modelling and simulation has become an essential part of the material development R&D cycle. Using molecular modelling, physical and chemical phenomena can be predicted ab initio, enabling the characterisation of the expected performance. As such models are too complex and computationally intensive for the simulation of final products, they must be embedded in a multi-scale approach so that, ultimately, the end use properties of a product can be predicted. Additionally, machine learning/AI technologies have to be taken into account more systematically across all process industries as part of this multi-scale approach.

Currently, the design of materials is not tightly connected to the design of the production processes that will lead to the production of these materials. Integrating process design and model-based materials design more tightly is envisioned as a design paradigm change. Safety and sustainability of the production processes and recycling/reuse can then be considered as factors in the materials design phase so that an early life cycle assessment is possible.

Specific targeted benefits are:

- **Reduced costs and improved efficiency of the R&D process** by applying digital R&D within early product/process design and development stages, which speed-up innovation and allow a more efficient “idea-to-market” process, including leveraging earlier experimental data/company knowledge in the experimental design phase;
- **Reduction of experimental effort** by moving towards a more and more model-supported material design process. Such a model-based approach will integrate a large variety of models, from ab-initio simulations on the atomic and molecular level to material models that can be integrated into the product design by the customers and to models that can describe the behaviour of the products and the materials in end-of-life disassembly, reuse and re-processing.
- **Faster development** by improved collaborations through digital R&D, which will also allow a quick response to market demands through integration of customers and value chains into the R&D-process and by creating an innovation ecosystem comprising SMEs, startups, academia, and the process industry.
- **Improved reproducibility of results** by applying digital R&D to analyse large volumes of data, increase the speed to scale-up due to the capacity to experiment faster and in accurate manner, whilst enhancing the capacity to handle more complex data and multi-parametric experiments.
- **More efficient, safe, and sustainable production processes** by early consideration of the production processes and feedstock into the product design, taking into account life cycle assessment, feedstock availability and variability, and health and safety issues (e.g., by considering the use of green solvents).
- **Disruptive production processes** by integration of digital technologies in all stages of the R&D process.
- **Data platforms to share and exchange knowledge**, skill, know-how, tools, experience and good practice provide effective communication among involved innovators/stakeholders, resulting in increasing the effectiveness and commercial benefits of their activities.

**Specific objectives**:

1. Materials design
   a. Further development and integration of modelling and simulation tools in the materials design process on the path towards a landscape of interoperable digital

tools from molecular simulation to LCA and end-of-use product and materials handling.

   b. Improvement of the efficiency of the materials design process and the computational tools used therein by integrating advanced design of experiments, data-based models and machine learning/AI. This includes the use of surrogate models that approximate computationally intensive model elements, novel forms of empirical models that are trained using experimental or end-use data, hybrid models that combine data-driven and physics-based model elements, and model-based design of experiments. The capability of performance-based simulations over extensive physical testing must be enhanced and in parallel multi-scale measurements and characterisation tools and methods must be improved.
   c. Development of digital technologies for knowledge- and data-driven collaborative R&D, based on the combination of fundamental models, machine learning and knowledge driven techniques. Conservation and activation of the available knowledge by the development of suitable representations and search algorithms, including literature, patents, open and proprietary data.
   d. Tools and methods for sharing of data and knowledge along the supply chain in the materials design process that provide scalable accessibility and protection of the data.
2. Integration of materials and formulations design with process design
   a. Include information about the production process and the feedstock into the materials design process early on to arrive at the must sustainable, efficient and safe production processes
   b. Develop more fundamental characterisations of the (secondary) resources as input for more flexible production processes so that the overall sustainability can be optimised.

**Table 31: Investment needs in € million – work in progress and subject to change[67]**

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 |
|---|---|---|---|---|
| 2020-2030 | Integrate computational tools (incl. data-based models, artificial intelligence) into materials design.<br>2021-2023<br>4 projects, €12<br><br>Characterisations of alternative feedstocks as input for more flexible production processes<br>2021-2023<br>3 projects, €6<br><br>New data platforms to share and exchange knowledge and good practice amongst R&D actors<br>2021-2023<br>3 projects, €6 | Tools and methods for sharing of data and knowledge along supply chains<br>4 projects, €12<br>2021-2028<br><br>Implementation of digital supported Life Cycle Assessment (LCA) methodologies and software including the early product development phases<br>4 projects, €24<br>2024-2027<br><br>Platforms for data sharing along innovation ecosystems to foster knowledge- and data-driven collaborative R&D<br>2024-2027<br>3 projects, €15<br><br>Digital technologies for materials and products optimisation including Machine Learning (ML), using data coming from the running process and from the product in use<br>4 projects, €12<br>2021-2028 | Integration of technologies previously developed for implementation of “digital twins” of products from the beginning of design phases<br>4 projects, €24<br>2024-2027<br><br>Digital technologies for full product eco-design by managing complex interactions between different supply chains<br>4 projects, €24<br>2024-2027<br><br>Software tools aiming at supporting fully model-base adaptative R&D process<br>4 projects, €24<br>2024-2027 | |

[67] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

### 6.15.2 Towards digital process development & engineering

Process design is increasingly done using faithful predictive simulation models of processes, pieces of equipment, and plants. However, several aspects still prevent the use of the full potential of the model-based approach: often, fundamental data, e.g. of thermodynamic properties or kinetics is missing and expensive to generate experimentally. Building fundamental models is a demanding process that absorbs the capacity of high-level experts over long periods of time, so that many process elements are not described by rigorous models. In many cases, model simulations are still computationally very demanding. Dynamic models that can describe the reaction to changeovers of products and feedstock or load changes e.g. in response to the availability of “green” electric power are usually not available. Models for the design phase are only rarely used in the production phase of the life cycle of the process, and information on the behaviour of the real plant and on its modifications is only rarely fed back to the design model. As a consequence, the experience from the operation of the designed plants and processes is not available, when similar plants are designed, or modifications are planned. Paving the path to digital twins of production processes that accompany the process throughout its life cycle so that the available information is used to the most to improve its sustainability and economic performance necessitates to address the following challenges:

- Large-scale predictive dynamic simulations based on sub-models of different types and granularities (from physics-based to data-driven or AI-based) that enable e.g. to evaluate the effect of changes of feedstock due to the recycling of materials in a circular economy
- Methods and mechanisms for dynamic model adaptation to the observed process behaviour during the full life cycle of the plants with minimum intervention by semi-automatic procedures
- Platforms for model exchange and model-reuse within and across companies and within the whole ecosystem of the process industries to reduce the modelling effort and broaden the scope of model-based process design. This must include standardised machine-readable ways of model annotation that provide sufficient information on the assumptions behind a model, its accuracy, and its limitations so that an automatic consistency check of the combination of sub-models from different sources to overall process models is possible.

Specific targeted benefits are:

- Digital Twin applied for digital process development and plant engineering will allow the efficient simulation of process parameters accelerating the design and the efficiency of the utilisation of plant assets;
- Digital twins contribute on higher safety of operations through prediction and early identification of possible root causes of major process disruptions;
- Going beyond process and plant operation improvements, offline and online supervised training of operation staff contributes to the efficiency and safety of the plant control and operations.

Specific objectives are:

The objective is to disruptively transform how process engineering is done today, by moving to fully model-based process design within the process industry including the objective to develop a digital twin ecosystem:

1. Development of large-scale predictive dynamic simulations based on sub-models of different types and granularities (from physics-based to data-driven or AI-based) that enable e.g. to evaluate the effect of changes of feedstock due to the recycling of materials in a circular economy;
2. Design and implementation of platforms for model exchange and model-reuse within and across companies and within the whole ecosystem of the process industries to reduce the modelling effort and broaden the scope of model-based process design. This must include standardised machine-readable ways of model annotation that provide enough information

on the assumptions behind a model, its accuracy, and its limitations so that an automatic consistency check of the combination of sub-models from different sources to overall process models is possible. What follows is all about using operational data to update models. It should be reduced to fewer items.

3. Development of methods and mechanisms for dynamic model adaptation to the observed process behaviour during the full life cycle of the plants (including retrofit) with minimum intervention by semi-automatic procedures.
    a. Develop and implement tools that allow vendor-neutral, simple, secure access to contextualised, cleaned operational data for analysis by process owners, suppliers, service companies and innovators.
    b. Development of methods and mechanisms for dynamic model adaptation to the observed process behaviour during the full life cycle of the plants (including retrofit) with minimum intervention by semi-automatic procedures.
4. Integrate Virtual Reality tools in a computationally efficient ways to enable real-time visualisation and large-scale scenario planning into digital twins.

In summary, the Innovation programme Towards digital process development & engineering is foreseen with:

**Table 32: Investment needs in € million – work in progress and subject to change[68]**

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 |
|---|---|---|---|---|
| **2020-2030** | | 2021-2024<br>Digital twins of large-scale production processes, including heterogenous (physics and data-based) models of different granularities<br>4 Projects – €20<br>Target TRL 6<br><br>2024 – 2027<br>Sector specific vendor-neutral model platforms<br>4 Projects – €20<br>Target TRL 5 | 2027 – 2030<br>Implementation and demonstration of vendor-neutral models<br>4 projects – €40<br>Target TRL 7 | |

## 6.16 Digitalisation of Plants

Industrial processes and related process chains are getting increasingly complex triggered by new products with new features and higher demands on the production plants, the need of higher production flexibility, flexibility towards alternative feedstocks (e.g. waste, biomass), the trend for more customised products, modular production approaches and manufacturing approaches to reach a lot size of 1.

New digital-enabled solutions are necessary to **improve process control and operations reliability**. These new solutions will not only further optimise the processes themselves but will also significantly improve production scheduling by considering product quality, energy, and resource efficiency. New cognitive tools need to be developed that will be driven by reliable process analytical technologies (PAT) and will make use of the process data and **provide high level supervisory control** while supporting the process operators and plant engineers within process industries. Next to generating added value in terms of efficiency and sustainability, cognitive applications must always ensure operation reliability and need to be **robust, flexible and transparent** to all users. Furthermore, they should be applicable without high customisation efforts and related costs.

Digitalisation of manufacturing and plant operations will be disruptive by **significantly reducing manual work and allowing for the efficient free-flow of information for improved decision**

[68] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

**making**. Allowing for upstream and downstream secure information sharing could also significantly impact process quality and predictive maintenance. Having data immediately available in the process plant that indicates the delivery of raw materials with key information such as timing, quality, and quantity means that the plant can **adjust their production schedule and recipe in real-time for additional throughput and efficiency of a quality product.** This improved product, along with the information, can then be delivered downstream for additional efficiency gains in every step of the value chain. **Efficiency gains in on-stream-time, raw material usage** and energy usage because of less rework and less waste in each production facility. This improvement will yield far-reaching, long-term benefits. PAT and data-based model innovation will also be reflected in the intelligent scheduling of maintenance activities and a reduction in unplanned outages which will add additional benefit to safety, energy usage and throughput as well as an improvement in spare part management and a reduction of safe stock.

As of today, not all processes/corresponding plants are fully understood and could be described in a suitable digitised way, a **full digital model of plant or process/plant operation** will be necessary to develop. Furthermore, the kind of plants and plant operations is highly different in different process industries: from some slow chemical processes (like a distillation tower or a cement kiln) with control cycles of minutes up to very fast mechanical processes (like steel or aluminium rolling mills) with control cycles in the milliseconds range.

At the very slow processes process control is in some cases still based on operator experience, because the existing models can only describe a part of the process or is in general too incorrect to allow a closed loop control. In such cases **Decision Support System** based on data or symbolic knowledge can help the operator to run the plant. On the other hand, newest model predictive control techniques based on complex, sometimes hybrid-models becoming state of the art, e.g. in chemical production plants. The target here is a **full control of single processes** with the aims of **improved product quality, optimal energy- and resource-efficiency and minimal production costs**. Important is also the coordination of the control of interconnected processes. Other fields for significant improvements by further digitalisation solutions are **production scheduling and maintenance operations**. One large disadvantage in this area is the fact, that both items are highly interconnected on the one hand but are operated completely independent and uncoordinated on the other because they are very often driven by different departments. A possible solution here could be a system of digital twins of products and processes where the digital twins are able to communicate to each other (e.g. like software agents) and are able to solve online optimisation problems on that way. Better inter-process scheduling plays an important role to reach higher resource and energy efficiencies. **Optimal maintenance strategies in combination with improved scheduling increases** the production yield (with the effect of better energy and resource efficiency) and reduces production costs. The final aim in both fields is the **self-driven and self-organising production with optimal resource efficiency.**

For the handling of complex plants in process industries the availability of online information about the plant, the process and intermediate or final product quality features is essential. Without these information process control, production scheduling, material allocation and maintenance actions are not possible. Therefore, **powerful and intelligent sensors or sensor networks** are necessary and solutions to handle the huge amounts of online-data coming from these sensors must be available. Additionally, these data must relate to relevant, sometimes unstructured context information.

Data lineage (data provenance) will play an increasing crucial role to manifest those bits of information as valid and reliable, on which important decisions are based. It will pave ground for trust-based data feeds with qualified and quantified certainty and uncertainty. This will also foster process automation, because the control system can now evaluate the reliability of its input data.

Highly connected to plant operation is the availability of **alternative energy from renewable sources**. Out of this reason solutions for the **flexible and adaptive use of different kinds of energy** and their coordination between different plants/sites/industries are necessary. Suitable optimisation strategies could help to find an optimal solution in this environment with once more contradictory demands.

The movement towards a circular economy as well as the utilisation of electric power from renewables will put much higher demands on the flexibility of the plants and processes, in terms of load variations, variations of feedstock, and variations of product specifications.

For all the above described tasks new, more powerful and fully integrated solutions are necessary which can only be reached by powerful digitalisation technologies. The aim must be to reach a highly flexible, easy to handle and generalised solutions **for the optimisation of processes and complete process chain of a company**, and even between companies and industries. **Digital Twins for plants, processes and products** which can communicate to each other in a highly flexible way e.g. to solve complex production problems in a **self-organised manner** are one part of the solution. By that, in 2050 a process enterprise will have access to accurate, curated and readily accessible operational data to support both routine (automated, autonomous) work flows and analytics-supported optimisation.

### 6.16.1 Optimised plant operations control towards highest quality products and fully energy, resource efficient and environmentally friendly plants

As mentioned above, in process industry a **large variety of different kinds of processes** can be found. In some cases, process control is still based on operator experience, because the existing models can only describe a part of the process or is in general too incorrect to allow a closed loop control. In such cases kinds of **Decision Support System** e.g. based on machine learning/AI technologies can help the operator to run the plant. **Advanced operator interfaces** are an important precondition therefore. On the other hand, newest model predictive control techniques based on complex, sometimes hybrid models is state of the art in parts of the process industry but not fully exploited up to now. Furthermore, “Machine Learning Control” is a new trend and enlarges the available tools for online process control. The target here is **a full and dynamic control of single processes** with the aims of improved product quality, optimal energy and resource efficiency, considering all environmental issues at minimal production costs. Additionally, the coordination and optimisation of the control of interconnected processes is an important topic. Regarding production scheduling a direct connection to IP 17.x is given here. One of the most important aspect is the field of control is the topic of **flexibility** in many aspects: flexibility in using different kinds of energy or raw materials with different properties, flexibility in reaching a lot size of 1 if needed or flexibility in using a different process route inside the company in case one plant runs currently a maintenance action.

Depending on the kind of process different **combinations of low-level control, direct product quality control and overall supervisory control solutions** in a cognitive manner are necessary to reach the final targets. In the overall supervisory control all environmental aspects like $CO_2$-emission, other pollutions, as well as energy and water consumption have to be integrated. Here new and disruptive techniques are necessary. On all the above level of control a **suitable combination of 1st principal models based on physical/chemical relationships and data-driven models** constructed by machine learning/AI approaches and semantic models could be a solution. Based on these models the scope of model-based control and model-based optimisation shall be enlarged to all possible areas. Here the interaction between operators/engineers with such solutions has to be considered and new techniques for operator interfaces have to be developed.

While product quality, production yield and costs are since a long time the main targets of process control, energy and resource efficiency as well as reduction of any kinds of pollutions didn't play in all industries a central role. Now **the integration of all resource efficiency and environmental aspects** have always to be considered:

*Energy:* Here solutions for the flexible and adaptive use of different kinds of energy and their coordination between different plants of a company are necessary. Additionally, connection to and coordination with external grids of renewable energy are highly necessary (see also innovation programme 6.2.1 Flexibility and demand response). The use of digital capabilities will provide industrial stable operations and grid stability in an increasing renewable energy landscape. E.g., intelligent prediction of energy consumption and energy availability by use of AI technologies like Machine learning solutions will play a significant role. Suitable optimisation strategies could help to find an optimal solution in this complex environment with in many cases contradictory demands. The final and most important objective is to reduce the energy usage of fossil fuels dramatically.

*Water:* In many plants of the process industry water plays an important role, as raw material/feedstock or as process water, e.g., for cooling purposes. On the other hand, clean drinking water will become one of the most challenging aspects for the future of humankind. Therefore, a full integration of control of water cycles into the overall process control of production plants is necessary to save water or to avoid water contamination wherever possible. Additionally, aspects of water purification have to be considered. Here flexible algorithms to support water operation decision making, risk management and water use considerations on integrated system level and based on suitable models have to be developed and implemented.

*Pollutions:* Directly connected to energy consumption of plants is the emission of $CO_2$ which has to be reduced drastically in the next years. Additionally, completely new production processes will be developed e.g. based on hydrogen instead of carbon usage for the process itself or as energy source and these processes have to be controlled in a suitable way. Furthermore, the integration of pollution aspects into process control of single plants as well as the optimal coordination of several plants of one company by interconnected control solutions will help to reduce $CO_2$ emissions. Beside $CO_2$ all other possible pollutions which effect the environment negatively have to be considered on the different levels of process control. Of course, this is highly depending on the nature of the plant.

*Waste:* The avoidance of any kind of production waste has to become an essential part of process control solutions. Therefore, suitable KPIs have to be developed and directly integrated in the above-mentioned supervisory control of single plants. In cases where waste can't be avoided because of process constraints the information about the waste, its ingredients and its amount have to be transferred to company or industry park wide waste stream management systems.

Digitalisation of process industry is directly connected to the topic of **Cyber Security**. The more all relevant processes and information flows are digitised the more the **risk of cyber-attacks** increases. It is not the task of this innovation programme to solve the general topic of security of IT solutions but the topic of risks in the field of **process safety based on cyber-attacks to process control** solutions coming from outside shall be addressed. All the above-mentioned necessary developments have to take this risk into account and solutions have to be found to detect as early as possible attacks to process control systems. Solutions could e.g. be based on the usage of domain knowledge about the implemented control solutions (e.g. in form of suitable models for the detection of abnormal process behaviour) in combination with Machine Learning techniques to differentiate between "normal" sensor fluctuations and artificial sensor signals which are caused by a cyber-attack.

An important role in all the above aspects plays the technology of **Digital Twins**, as well for processes as also for products. The Digital Twin technology itself **has to be further developed** to fulfil all demands of process control purposes (innovation programme 6.16.1 Optimised plant operations control towards highest quality products and fully energy, resource efficient and environmentally friendly plants). Digital Twins are not only passive elements like a combination of different types of models of plant, process or product in connection with process data (sometimes also named the Digital Shadow of the product), it is necessary to **integrate active and agile elements** (e.g. based on software agents) which are able to communicate among each other to become the Digital Twin a very powerful tool to solve complex and distributed optimisation problems. To enable Digital Twins to orient themselves in real world environments **semantic models** of the complete production flow and many of its aspects are essential. Finally, an ecosystem of agile Digital Twins suitable for all the above-mentioned tasks has to be developed. In such a way, Digital Twins can achieve the above stated vision of a self-driven and self-organising production.

Modern process technologies have become more complex, **requiring highly-qualified personnel** to handle complex information streams. At the same time the importance of predictive maintenance increases to reduce unscheduled downtimes, identify (critical) process states and assess of wear and tear of equipment. Intuitive human machine interfaces to efficiently support people at the workplace thus become increasingly important. Technologies like **smart glasses, augmented reality, data analytics, combined with smart hand-held devices provide** a hitherto unknown availability of information, visualisation and interaction possibilities. The potential of the combinations of these technologies still must be explored. There will be a paradigm shift from the conventional control room to the provision of smart information, visualisation and offsite interaction both for the operator or the maintenance crew on the site. By providing the pre-processed information, tailored to the current situation, decision taking in complex situations and safety at work will be strongly enhanced. This will be complemented by knowledge management technologies to represent either written (documented) information and/or the knowledge of experienced operators.

In the environment of '**Machine-to-Machine' and 'Human-to-Machine' (M2M, H2M**), 'humans-in-the-loop' concept is always central for operation control and management in the operation of plants belonging to process industries. Digital support of operators encompasses the optimum use of their knowledge and experience and providing support combining situation awareness and information provided by advanced control algorithms and optimisation. Such an approach empowers operators' actions through the extended adoption of wearable systems, augmented reality technologies and virtual reality-based training, improving dramatically safety and effectiveness in operations in the same time.

The objectives of this innovation programme can be described as following:

- Full dynamic and model-based control of single processes with the targets of improved product quality, optimal energy and resource efficiency and considering all environmental issues at minimal production costs.
- Coordination and optimisation of the control of interconnected processes in a process chain by a suitable combination of low-level control, direct product quality control and overall supervisory control solutions.

- Decision support systems for all processes and process chains where model-based online control isn't possible.
- Early detection of possible cyber-attacks to process control systems and starting of suitable counteractions as soon as possible.
- Development of an ecosystem of suitable Digital Twins of plants, processes and products to realise the above-mentioned tasks.
- Define the role of humans in the operation of plants, how can their knowledge and experience be optimally combined with advanced control algorithms and optimisation, how can humans supervise complex computer-based solutions.
- Design more intuitive systems for operators (e.g. dynamic data dashboards).
- Virtual environment/virtual reality for training of full production processes. Digital twins and plant models for learning purposes.

**Table 33: Investment needs in € million – work in progress and subject to change[69]**

| Timing | TRL 1-3 | TRL 4-6 | TRL 7-8 | 9 |
|---|---|---|---|---|
| **2020-2030** | Ecosystem of Digital Twins suitable for process control purposes (2021-2023), 2 projects, €16<br><br>Machine learning/AI techniques suitable for cognitive process control (2021-2024), 4 projects, €20<br><br>Techniques for the detection of Cyber-attacks on process control systems and suitable counteractions (2021-2023), 3 projects, €12 | Decision Support Systems and suitable operator interfaces for class of processes which can not yet be operated fully automatically (2021-2025), 3 projects, €15<br><br>Fully dynamic cognitive control of single processes integrating all aspects (quality, costs, environ-ment), (2022-2026), 4 projects, €24<br><br>Coordination and optimisation of control of interconnected processes (2023-2026), 4 projects, €24<br><br>Integration of Anti-Cyber-Attack solutions into process control system (2023-2025), 2 projects, €10 | Demonstration of cognitive control of typical classes of processes (2026-028), 3 projects, €24<br><br>Demonstration of cognitive supervisory control of interconnected plants, (2027-2030), 4 projects, €32 | |

### 6.16.2 Intelligent sensors and sensor networks, data processing and equipment monitoring to assess the state of equipment and materials

For the handling of complex plants in process industries the availability of **online information** about the plant, the process, the environment of the process and intermediate or final product quality features is essential. Without these information process control, production scheduling, material allocation, energy and pollution reduction and maintenance actions are not possible. Therefore, powerful and intelligent online sensors or sensor networks are necessary and solutions to handle the huge amounts of online-data coming from these sensors and to extract useful knowledge out of them have to be available. Additionally, these data have to be connected with relevant, sometimes unstructured context information.

The focus of the sensor developments should be on **properties of raw materials** as well as on intermediate and final products. Furthermore, sensors to fully describe the **environmental aspects of plants** and processes like energy usage and any kind of pollution as well as **sensors necessary for predictive maintenance** in real-time have to be developed. Wherever possible

[69] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

sensors or sensors networks should work **wireless**, must be proved at an industrial scale and a minimum lifetime of 5 years. Improvement of connectivity by using 5G is necessary to increase the speed at which data can be accessed. Real-time availability of the structured data generated by the sensors with a standard format is crucial for advancement. 5G must also be the standard communication protocol at the industrial level and should be overcome by the next high-speed protocol generation which utilises the same backbone for ease of implementation.

Another objective is to solve the "**industrial Big Data problem**" as basis to develop the cognitive digital plant by 2050. The process industry needs to move from data to information to knowledge to control. Over time the process industry has amassed an incomprehensible amount of data where only a small percentage is actually being utilised. Transformation of data into smart and useful information/knowledge will require the developing of hard and soft solutions eventually based on new computing techniques. Highly important here are first of all **new and intelligent pre-processing techniques** like e.g. checking of data quality before moving it into data models. The availability of online information about the industrial areas, the process and intermediate or final product quality features as well as recipe management is essential. With this information process control, production scheduling, material allocation and maintenance actions can be improved by new computing techniques, a suitable combination of different modelling technologies and AI methods like machine learning techniques (and here especially "reinforcement learning") play an important role.

To realise suitable maintenance actions one precondition is to **detect** as many **equipment failures** automatically as possible with the aim to have zero unplanned outages due to hardware asset malfunction by 2050. Traditional asset condition monitoring coupled with Machine Learning joined with the capability of Big Data analysis will bring a **new scenario into plant maintenance**. Manual and periodical campaigns for equipment health analysis will no longer be necessary bringing opportunities for using resources in a more efficient way. Abnormal detection, alarms and maintenance scheduling will be linked together for avoiding unplanned stoppages due to machinery failures. To reach the optimal effect of **new maintenance strategies** a powerful coordination between maintenance and production scheduling (refer to IP 17.x.) is essential. One large disadvantage in this area is the fact, that both items are highly interconnected on the one hand but are operated completely independent and uncoordinated on the other because they are very often driven by different departments. A possible solution here could be a **system of digital twins of products and processes** which is able to solve online optimisation problems and offers the possibility of self-organised production systems.

The above-mentioned plant monitoring regarding equipment failure has to be expanded by other **monitoring tasks regarding environmental targets** like energy, raw material and process water consumption, $CO_2$-emissions, other pollutants and any kinds of waste. These monitoring results are on the one hand the inputs for the supervisory control solutions of single plants and process chains described in 16.1 and on the other hand the basis for a factory and site level wide monitoring of the whole production efficiency and many environmental aspects. Parameters of a Life Cycle Analysis (LCA) of the products have furthermore to be integrated in the plant monitoring strategy.

The objectives specific for this innovation programme are:

- Powerful and intelligent online sensors or sensor networks (wireless wherever possible) with focus to properties of raw materials as well as on intermediate and final products, sensors to measure environmental aspects of plants and processes like energy usage and any kind of pollution, sensors necessary for predictive maintenance.
- Solutions for automatic pre-processing of the large amounts of data coming from plants, processes and products and method to extract automatically and in real-time useful information and knowledge out of it.
- Solutions to detect possible equipment failures early automatically by intelligent condition monitoring system, e.g., empowered by machine learning/AI technologies and techniques

for predictive/prescriptive maintenance actions based on this information. Coordination of all maintenance actions with production scheduling of the whole process chain (connection to innovation programme, 6.17.2 Towards fully connected process industries – scheduling across plant networks/sites/industries/municipalities - industrial symbiosis).

- Expanding of plant/process monitoring systems by methods to always reveal the full environmental footprint of the running process in real time and initiation of counteractions in any case of deviation from the optimal conditions.
- Integration of LCA aspects into the plant and site-wide monitoring strategies.

The programming and investment needs to target these objectives are shown below

**Table 34: Investment needs in € million – work in progress and subject to change**[70]

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 |
|---|---|---|---|---|
| **2020-2030** | Fully automatic pre-processing of all necessary data (2021-2023), 2 projects, €16<br><br>Automatic real-time extraction of knowledge from huge amounts of process data (2021-2024), 3 projects, €15<br><br>Intelligent sensors and sensor networks for products, processes, plants and environmental aspects (2021-2024), 3 projects, €18 | Early detection of equipment failures and techniques for predictive/ prescriptive maintenance actions (2022-2025), 4 projects, €20<br><br>Expanding process monitoring system by all relevant environmental and LCA aspects and initiation of counteractions (2021-2025), 2 projects, €12 | Coordination of maintenance actions with production scheduling (2025-2028), 2 projects, €12<br><br>Integrated, cognitive and site-wide maintenance solutions (2026-2030), 3 projects, €24 | |



[70] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## 6.17 Digitalisation of connected processes and supply chains

This Innovation Area focuses of digitalisation of within supply chains and across supply chains. The changes will need to happen horizontally and cover the entire life cycle of materials, including every step of sourcing, production, distribution, and end-of-lifetime processing, across the entire supply chain.

Supply chain digitalisation can occur on different levels:

1. Supply chains within a company or single production processes: planning and scheduling can be improved to optimise efficiency and reliability of supply in the presence of uncertainties on raw materials, prices or resources;

2. Integration of the upstream supply chain: procurement and predicted deliveries are integrated into the planning to optimise not only on company level but on the full upstream supply chain level to achieve efficiency improvements that reduce the carbon footprint;

3. Full supply chain: integrated optimisation of logistics, energy, and industrial symbiosis but now also with downstream actors. Additionally, it includes integrated waste management (waste water treatment, thermal treatment, other by-products, etc.) optimisation

At the first level (supply chains within a company or production process), **planning and scheduling can be improved to optimise efficiency and reliability** of supply in the presence of uncertainties on raw materials, prices or resources. This includes a mixed optimisation of batch trajectories and batch production scheduling (trade-off between the maximisation of throughput and resource- and energy efficiency). Here a clear overlap to the innovation area "plant & plant operation" exists (see Section 6.16). Additionally, the task of optimised pre-production planning starting with customer orders must be mentioned explicitly.

At the second level, (integration of the upstream supply chain) **procurement** and **predicted deliveries** are integrated into the planning to optimise not only on company level but on the full upstream supply chain level to **achieve efficiency improvements that reduce the carbon footprint.** A similar integration can be achieved with procurement of energy (electricity, heat, others), to enable demand-side management.

Furthermore, industrial **symbiosis** (see also Sections 0 and □) can be coordinated digitally to couple production unit/sites under different ownership **to maximise overall efficiencies of symbiotic industrial networks.** Finally, real-time transfer of product information enables use of resources with variable quality.

Finally, the full supply chain level adds the downstream element to the system. This includes integrated optimisation of logistics, energy, and industrial symbiosis as described under level 2, but now also with **downstream actors**. Additionally, it includes integrated waste management (waste water treatment, thermal treatment, other by-products, etc.) optimisation. When covering the full supply chain, it also enables the **transfer of information across the supply chain in real time**. This enables agile demand-driven supply chains, customised product optimised for sustainability, and facilitation of reuse and recycling by digital fingerprints/digital twins of products along the supply chain. Furthermore, this includes the reverse optimisation of the process chain of the material production, by e.g., product quality data or feedback coming from the customer, with the aim to increase the yield and to improve the resource efficiency.

Developments at all three levels will also be reflected in the scheduling of maintenance activities and a reduction in unplanned outages which will add additional benefits to safety, energy usage and throughput.

### 6.17.1 Towards fully autonomous scheduled production processes and integrated supply chains

This innovation programme aims to find solutions for integrated planning, scheduling and control within plants and supply chains. This will cover the first two levels as described above.

Supply chains can be very complex, with recycle loops both within the plants and sites but also further to the assembly of the final products and their recycling. The residence time of the materials within this chain may be up to months. All along the supply chains, the goal is to avoid an accumulation of material and to produce just in time and on spec all the time, but also efficiently. Customer demands are becoming more volatile which pushes the process industry to more agile production concepts which creates a tension with the request for higher efficiency. With the introduction of renewables into the electric grid and the switch to the use of electric power from renewables as a main source of energy, a further dimension of flexibility is opened up, as the consumption of electric power must be adapted to the availability of "green" power, both to reduce the $CO_2$ footprint and to reduce the cost of energy.

All these factors lead to an increasing pressure to manage processing and supply chains dynamically such that energy and resource efficiency and an agile response to changing customer demands as well as prices for raw materials and energy and availability of green power are realised simultaneously. Digitalisation is the key to achieving this target.

The specific objectives are:

1. Solutions for integrated planning, scheduling, and control within plants
    a. Improved digital-enabled planning and scheduling to optimise efficiency and reliability of supply in the presence of uncertainties on raw materials, prices, resources, etc.
    b. Data integration and full transparency of the situation along the supply chain, visualisation concepts
    c. Mixed optimisation of batch-trajectories and batch-production schedules, addressing the trade-off between the maximisation of throughput and resource- and energy-efficiency
    d. Integration of predictive maintenance with planning and production scheduling
    e. Integration of production planning and scheduling with the operation of utilities (e.g. steam, electric power, waste treatment) and electric-power procurement, adaptation to the supply of electric-power from renewables, demand-side management
    f. Integrated management of production with waste and wastewater treatment
2. Integration of planning and scheduling along the supply chain
    a. Integration of the upstream supply chain
    b. Integration of downstream logistics
    c. Real-time integrated logistics, procurement, and production optimisation
    d. Real-time cradle-to-gate resource efficiency and LCA monitoring and optimisation
3. Data integration along the supply chain and across sectors
    a. Concepts for the provision of information on products and production processes along the supply chain that are compatible with the protection of IP and commercial interests and development of platforms that implement these concepts
    b. Facilitation of reuse and recycling by digital fingerprints of products along the supply chain, based on standardised product descriptions.
    c. Real-time characterisation of waste streams enabling an increase of the use of secondary materials.
4.

The programming and investment needs to target these objectives are shown below

**Table 35: Investment needs in € million – work in progress and subject to change**[71]

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 |
|---|---|---|---|---|
| **2020-2030** | Concepts for data sharing along the supply chain in the process industries<br>2021-2023<br>4 projects, €12<br><br>Concepts and standards for digital fingerprints of materials and products<br>2021-2023<br>3 projects, €6<br>(see also IP5) | Integrated planning and scheduling of plants and sites<br>4 projects, €24<br>2021-2028<br><br>Integration of planning and scheduling along the supply chain<br>4 projects, €24<br>2024-2027<br><br>Real-time REI and LCA analysis from cradle to gate<br>3 projects, €15<br>2021-2024<br><br>Platforms for data sharing along the supply chain<br>2024-2027<br>3 projects, €18<br><br>Information transfer along the supply chain<br>3 projects, €15<br>2024-2027 | Integrated planning and scheduling of plants and sites<br>3 projects, €30<br>2025 – 2030 (2 calls)<br><br>Real-time resource efficiency and LCA monitoring from cradle to gate<br>2 demonstrations, €16<br>2025-2027<br><br>Integration of planning and scheduling along the supply chain<br>2 projects, €16<br>2028-2030<br><br>Demonstration of digitally integrated supply chains with minimised carbon footprint<br>3 projects, €30<br>2028-2030 | |

### 6.17.2 Towards fully connected process industries – scheduling across plant networks/sites/industries/municipalities - industrial symbiosis

This innovation programme focuses on the development of digital technologies that enable urban-industrial symbiosis so that material cycles can be closed within the industrial sector as well as between the consumers and industry, and energy and water are used in the most efficient manner. This covers level 3 as described in the introduction to this chapter. Efficient urban-industrial symbiosis requires a continuous adaptation of all parties involved to variations of supply and demand such that the overall energy and resource efficiency is maximised, the environmental impact is minimised, and all partners have economic advantages.
The integrated operation, planning and scheduling of large interconnected industrial plants and sites is already a major challenge (see the previous innovation programme). In industrial symbiosis, companies with individual business goals and both technical and economic constraints about which they do not want to share information freely are tightly connected, so an overarching coordination and distribution of benefits is becoming necessary. When progressing to urban-industrial symbiosis, uncontrollable and partly unforeseeable behaviours of consumers and the presence of complex connecting infrastructures (e.g., the collection and sorting of waste streams) makes an integrated management even more complex. Digitalisation is key to handling these challenges in order to arrive at integrated, energy and resource efficient, environmentally benign and economically competitive systems.

**The digitalisation of industrial symbiosis** currently is at TRL levels of 2-4/5. Within the SPIRE-CCNI programme, solutions for the systematic investigation of options for industrial symbiosis have already been developed. These must be rolled out to real applications, in particular in the hubs for circularity within the next years. Solutions for the real-time management and optimisation of connected production sites beyond the borders of individual companies have reached only low TRL-levels of 2-3. Also, the legal side of such collaborations needs to be explored. The demonstration of first prototypes of integrated management solutions should be

[71] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

achieved until 2025, roll-out of digital solutions the in hubs of circularity until 2030. Integrated water management between industrial sites, re-using waste water streams where possible to reduce the intake of drinking or purified water is a field which also promises reductions of the consumption of energy and resources and must be supported by digital technologies.

**Urban-industrial symbiosis** is still at a small fraction of its full potential. The most developed element is the use of industrial waste heat by municipalities. Better integrated management by digitalisation will lead to further improvements of the efficiency of the heat networks. Integrated waste-water management also can quite easily be extended to urban-industrial symbiosis. The reuse of urban waste by the process industry is no developed much yet. Recycling of complex materials from urban waste such as plastics critically depends on the separation of the waste streams into fractions that can be treated and reused efficiently. Tracking of materials and digital passports of end-products are therefore of crucial importance. Digitalisation of the separation of the waste streams is a must. The development of efficient technologies and digitised value chains from the collection of waste to the reuse of the materials in production processes will proceed from streams that can be handled relatively easily and efficiently with technologies that have reached TRL 4 or higher already (i.e., relatively pure input streams that can be processed to valuable raw materials in an efficient manner as e.g., PET streams) to more complex materials. Digital technologies must be developed in sync with the progress in the underlying processing technologies, and as enablers of more efficient separation and re-processing technologies.

In the long run, further developments of the digital support technologies for urban-industrial symbiosis will address the challenges that arise when urban-industrial symbiosis is broadened and deepened.

This IP aims to achieve:

1. Integrated real-time systems management for urban-industrial symbiosis
    a. Digitalisation of integrated industrial and urban-industrial water and waste-water treatment and distribution systems and of the utilisation of waste heat by industry and municipalities. The focus will be on the connection of presently separate management and control systems and the introduction of an overarching real-time management to increase the efficiency of the overall networks.
    b. Integrated real-time management and optimisation solutions for connected production units under different ownership to realise optimum material and energy efficiency of the overall network and at the same time maintain flexibility. The solutions must be compatible with anti-trust regulations and provide mechanisms to handle conflicts of interest and to distribute the benefits between the partners in a fair manner. Therefore legal, economic and organisational aspects have to be taken into account.
2. Digitalisation of the classification and sorting of waste streams
    a. Advanced affordable sensing capabilities for industrial symbiosis, providing real-time feedback on the composition of the streams that are exchanged
    b. Advanced sensing for the sorting of waste, for example of plastic waste, minerals, steel scrap and non-ferro metals.
    c. Digitalisation of the full value chain from the ingoing waste streams to their processing and the delivery of feedstock to the process industries so that the composition of the streams of the processing units is predictable and the whole chain can be operated in the most efficient manner.
3. Digital technologies for the tracing of materials and real-time brokerage of waste streams
    a. Full tracking of material compositions from the first production steps to the end products and real-time access to this information at any point in time of the life cycle of the products, if needed secured by the use of digital ledger technologies.
    b. Standardised formats for the digital characterisation of materials

c. Information systems that provide full and transparent information on all major waste streams and facilitate the exchange of these streams for material re-processing or reuse.

The programming and investment needs are shown below.

**Table 36: Investment needs in € million – work in progress and subject to change**[72]

| Timing | TRL 1-3 | 4-6 | 7-8 | 9 | Non-technological |
|---|---|---|---|---|---|
| 2020-2030 | Concepts for full digitalisation of plastic recycling value chains<br>4 Projects, €12<br>2021-2024<br><br>Tracking of material compositions – concepts and data formats<br>3 projects, €9 (could be CSA)<br>2021-2023 | Real-time management of waste-water and waste heat networks<br>2021-2025<br>4 projects, €24<br><br>Real-time management and optimisation of industrial symbiosis<br>First call to reach TRL 5 by 2024<br>4 projects, €16<br>Second call to reach TRL 6/7 by 2028<br>3 Projects, €18<br><br>Advanced sensing and automation for recycling of materials<br>2021-2025<br>6 projects, €30<br><br>Full digitalisation of materials recycling value chains<br>2025-2028<br>4 projects, €24<br><br>Prototypes for material tracing along the value chain<br>4 projects, €20<br>2024-2027<br><br>Information platforms on waste streams in Europe<br>2021-2024<br>3 projects, €18 | Real-world application of systems for the support of industrial symbiosis in hubs for circularity<br>2021-2025<br>€18<br><br>Real-time management and optimisation of industrial symbiosis<br>2025-2028<br>3 projects 18 M€<br>Advanced sensing for industrial symbiosis<br>2021-2025<br>€24<br><br>Advanced sensing and automation for recycling of materials<br>four projects €32<br><br>Platforms for material tracing<br>2028-2030<br>three projects, €30<br><br>Information platforms on waste streams in Europe<br>2 projects<br>€20 | Real-time management of wastewater and waste heat networks<br>DEMO<br>2026-2028<br>€18, 2 projects | Legal and business aspects of industrial symbiosis<br>CSA €1.5<br>2021-2023<br><br>Standardised formats for materials tracking<br>2024-2027<br>1 project<br>€4<br><br>Business concepts for information platforms for waste streams in Europe<br>2022-2023<br>CSA<br>€1,5 |

[72] Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

# 7 Annex B: Process to arrive at this roadmap

*<<this will be developed after the stakeholder consultation>>*

## 7.1 Process

Picture of how the process went on a timeline

## 7.2 Visions Group

## 7.3 Working Groups

## 7.4 Associations

## 7.5 Stakeholder interaction

Explaining all the interaction

- Vision workshop
- Booklet
- Stakeholder consultation
- Stakeholder workshop

## 7.6 Governance

# 8 Annex C: TRL definitions

| TRL level | Definition |
|---|---|
| **1** | Basic principles observed |
| **2** | Technology concept formulated |
| **3** | Experimental proof of concept |
| **4** | Technology validated in lab |
| **5** | Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies) |
| **6** | Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies) |
| **7** | System prototype demonstration in operational environment |
| **8** | System complete and qualified |
| **9** | Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space) |

The TRLs are defined as in Horizon2020 (European Commission, 2014).

# 9 Annex D: Energy and carbon price assumptions

In the innovation programmes consistent energy and carbon prices assumptions are used where possible to estimate impacts.

The following values are used:

| Price | Price in 2050 | Unit |
|---|---|---|
| **Electricity price** | 16 | €/GJ |
| **Natural gas price** | 9.4 | €/GJ |
| **Carbon price** | 25 | €/t$CO_2$ |

Electricity and gas prices are based on Eurostat data from 2018 and 2016, respectively. For gas the non-household price for consumption level between 1 and 4 million GJ/year is used (band I5) because this is most representative for process industry. Many installations will consume more, but as reporting of energy consumption statistics is voluntary for band I6, there are many data gaps. Only the “energy and supply” and “network costs” components are included because most process industries are exempt from most taxes and levies. 2018 was used because this is the most recent data point.

For electricity the non-household price for consumption level between 70 and 150 GWh/year is used (band IF) because this is most representative for process industry. Many installations will consume more, but as reporting of energy consumption statistics is voluntary for band IG, there are many data gaps. Only the “energy and supply” and “network costs” components are included because most process industries are exempt from most taxes and levies. 2016 was used because this is the most recent data point.

For both gas and electricity, the projected price change towards 2050 was based on the report that was used as input for the EC long-term strategy (ICF & Fraunhofer ISI, 2019). This shows that electricity prices are around 2015 levels in 2050 (0% growth) and gas prices increase by 45% from 2015 to 2050. This is equivalent to a compound annual growth rate (CAGR) of 1.1% per year. This CAGR is used to calculate the price increase from 2016 to 2050.

For the carbon price, many projections exist for 2050. However, as this is only used in this report to quantify competitiveness, assuming a high carbon price would make it more difficult to interpret the numbers. Therefore, a carbon price of 25 €/tCO2 is used, which is in line with the carbon prices of this year (i.e. 2019).

# 10 Annex E: Mapping of SPIRE projects to the innovation areas

| Innovation area | Innovation programmes | Most relevant Horizon Europe intervention areas | SPIRE H2020 projects that is built upon |
|---|---|---|---|
| **Integrating renewable energy carriers** | a/ Integration of renewables<br>b/ Integration of bio-energy waste and other new fuels<br>c/ Competitive hybrid transition to low-carbon industrial energy supply | Low-Carbon and Clean Industries<br>Energy Supply<br>Energy Storage<br>Emerging Enabling Technologies<br>Manufacturing Technologies<br>Energy Systems and Grids<br>Key Digital Technologies | TASIO<br>ADREM<br>TERRA<br>SteamBIO<br>Indus3Es<br>I-THERM<br>SUSPIRE<br>DRYF<br>ETEKINA<br>DESTINY |
| **Enhancing energy flexibility and diversity** | a/ Flexibility and demand response | | |
| **Enhanced utilisation of different grades of heat** | a/ Heat exchange optimisation | | |
| **Integration of hydrogen production, use and storage** | a/ Alternative routes for the production of hydrogen<br>b/ Introducing no emission hydrogen in the industrial processes<br>c/ Storage of hydrogen | | |
| **Electrification of heating processes** | a/ Electricity to upgrade waste heat<br>b/ Other electricity-based heating processes | Low-Carbon and Clean Industries<br>Emerging Enabling Technologies<br>Energy Supply<br>Energy Storage<br>Energy Systems and Grids | PRODIAS<br>ROMEO<br>ADIR<br>REE4EU<br>REMAGHIC<br>IbD<br>SIDERWIN<br>LIBERATE<br>PERFORM<br>MEMERE<br>PRINT3CREDIT |
| **Electrification to directly drive processes** | a/ Electrochemical conversion<br>b/ Electrically-driven separation | | |
| **Capture & purification of CO2** | a/ Flexible CO2 capture and purification technologies | Low-Carbon and Clean Industries<br>Emerging Enabling Technologies<br>Energy Supply<br>Circular Industries<br>Energy Storage | MefCO2<br>CarbonNext<br>RESME<br>ICO2CHEM<br>RECO2DE<br>CARBON4PUR<br>CO2-EXIDE<br>OCEAN<br>CO2MOS<br>Ecoco2 |
| **CO2 to minerals** | a/ CO2 valorisation during concrete production<br>b/ Circular construction materials by re-carbonation<br>c/ Natural materials mineralisation (e.g. olivine carbonating CO2) | | |
| **CO2 valorisation to chemicals, polymers & fuels** | a/ Direct utilisation of sunlight (Artificial photosynthesis)<br>b/ Catalytic conversion of CO2 (excl. photocatalytic and direct use in polymers)<br>c/ CO2 (and CO2/CO) to polymers<br>d/ CO captured from industrial waste gases to chemicals and fuels | | |

| | | | |
|---|---|---|---|
| **Disruptive processes for optimised use of virgin and secondary resources** | a/ Advanced catalysis providing resource flexibility and lower energy inputs through alternative chemical pathways<br>b/ Complete reuse of water and valorisation of the materials contained<br>c/ Innovative processes to maximise use of secondary raw materials<br>d/ Breakthrough process design for improved energy and resource efficiency | Low-Carbon and Clean Industries<br>Advanced Materials<br>Circular Industries<br>Key Digital Technologies<br>Manufacturing Technologies<br>Buildings and Industrial Facilities in Energy Transition | MobileFLIP<br>INSPRE WATER<br>SPOTVIEW<br>ZERO-BRINE<br>REWACEM<br>BIO4PRODUCTS<br>KARMA2020<br>REHAP<br>IMPROOF<br>VULKANO<br>DREAM<br>INSPIRE<br>ENSUREAL<br>SUPREME<br>MORSE<br>NOVUM<br>ECCO<br>PORTABLECRACK<br>SIMPLIFY<br>CIRMET |
| **Minimising the environmental footprint of materials** | a/ Innovative materials of process industries<br>b/ Inherent recyclability of materials | | |
| **Process technologies for Industrial-Urban Symbiosis** | a/ Demonstration of Industrial-Urban Symbiosis | Circular Industries<br>Communities and Cities<br>Low-Carbon and Clean Industries<br>Buildings and Industrial Facilities in Energy Transition<br>Key Digital Technologies | EPOS<br>Symbioptima<br>CABRISS<br>FISSAC<br>RESYNTEX<br>RESLAG<br>SHAREBOX<br>BAMB<br>CIRCPACK<br>ECOBULK<br>FIBEREUSE<br>POLYNSPIRE<br>MULTICYCLE<br>PLASTICIRCLE<br>POLYCE<br>DEMETO<br>SPRING<br>HARMONI<br>SCALER<br>BAMBOO<br>ICAREPLAST<br>ISOPREP<br>MMATWO<br>C2Fuel<br>REACT<br>NONTOX<br>PLAST2bCLEANED<br>REMADYL<br>CIRCULAR<br>FLOORING<br>CREATOR<br>EMB3Rs<br>So What |
| **Business-models & demonstration of I-US** | a/ Communities of Practice<br>b/ Development of Hubs of Circularity | | |
| **Digitalisation of process/product R&D** | a/ Towards digitally supported design of environmentally benign high-performance materials<br>b/ Towards digital process development & engineering | Key Digital Technologies<br>AI and Robots<br>Manufacturing technologies<br>Circular Industries<br>Low-Carbon and Clean Industries | MAESTRI<br>CONSENS<br>DISIRE<br>ICSpec<br>ProPAT<br>SHAREBOX<br>RECOBA<br>COPRO<br>Monsoon<br>FUDIPO<br>SMARTREC |
| **Digitalisation of plants** | a/ Optimised plant operations control towards highest quality products and fully energy, resource efficient and environmentally friendly plants<br>b/ Intelligent sensors and sensor networks, data processing and equipment monitoring to assess | | |

| | | | |
|---|---|---|---|
| | the state of equipment and materials | | |
| **Digitalisation of connected processes and supply chains** | a/ Towards fully autonomous scheduled production processes and integrated supply chains<br>b/ Towards fully connected process industries – scheduling across plant networks/sites/ industries/ municipalities - industrial symbiosis | | |

# 11 Annex F: References


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