



## Processes4Planet Roadmap Update

Update: 4 January 2021

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# P4Planet 2050 Roadmap

## Preface

### Document status

This report was prepared for A.SPIRE, the European Association which is committed to manage and implement the SPIRE (Sustainable Process Industry through Resource and Energy Efficiency) Public-Private Partnership. SPIRE will transition to a new name under Horizon Europe. The final name has not been selected yet, and therefore in this document the preliminary name **Processes4Planet** is used to refer to SPIRE under Horizon Europe

The report has been produced based on inputs from and in close cooperation with A.SPIRE. Important contributions were provided by the seven working groups (chairs and co-chairs), IRIAG, the Board of Directors and the core team. Furthermore, input from the sectors and companies in A.SPIRE was received through the stakeholder consultation, the stakeholder workshop and direct communication.

Navigant, a Guidehouse company, provided analytical and process support.

Note that, although most of the roadmap is final, two items will be added later:

- the “marbles” (which are still being discussed by the SPIRE sectors) will be added later in chapter 4
- Section 3.5

Furthermore, this roadmap is intended to be regularly updated to reflect new developments, insights and stakeholder input.



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### How to read this report

The **executive summary** provides a high-level summary of this roadmap (e.g. for policymakers).

The **main body** of the report provides more detail. It explains the rationale behind the roadmap and showcases the innovation areas and programmes that are included. The roadmap is synthesized to draw conclusions. This is written as much as possible for non-technical readers.

The **appendices** provide among other things the details of the individual innovation programmes in each innovation area and the specific innovation activities that are needed. They also present investment estimates, and boundary conditions for successful execution of the innovation programmes. The appendices are written for more technical readers.

### Disclaimers

Navigant Netherlands B.V. (“Navigant”) contributed to this report considering the information made available by A.SPIRE and its stakeholders. Navigant relied on information supplied by A.SPIRE and its advisers without audit or verification. Navigant assumes that all information furnished is complete and accurate. Navigant and A.SPIRE are not responsible and give no warranties or guarantees, expressed or implied, for the use that might be made of this report.

The **scope** of the roadmap is limited to cross sectorial innovations and the roadmap is intended to complement sector-specific innovations and currently available technologies that can already be implemented.

**Investment numbers** given in Appendix A are estimated without having concrete projects in mind and are not being informed by current SPIRE programmes, including these current SPIRE programmes mentioned in the same innovation programme.

**Competitiveness calculations** have been performed for some of the innovations. They are intended to illustrate the potential competitiveness of technologies, but as they are based on just one set of prices for the various energy carriers / carbon, they are intended as *illustrative* calculations only.

**Technology readiness levels** are difficult to define (especially using information from the public domain). Therefore, the TRL estimates for technologies in this roadmap are indicative only and may not always reflect the most up-to-date information.

# 1 Executive summary

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*European process industries stand on the brink of a great transformation to become circular and climate neutral by 2050. This roadmap details Processes4Planet's unique collaborative approach to deliver the cross-sectorial innovation that is essential to this transformation.*

The **European Green Deal** (European Commission, 2019)[1] is a game changer for our society at large, and for the European process industries in particular. Europe aims to reach climate neutrality<sup>1[OBJ]</sup> and a circular economy by 2050. Europe aims to reach climate neutrality<sup>2[OBJ]</sup> and a circular economy by 2050.

This goal cannot be achieved without the process industries. They convert primary raw materials and secondary resources into materials that are used in the manufacturing industry to make products or are used directly as products (for example in the case of roof tiles). The process industry also converts fossil and increasingly renewable resources into energy products (fuels) and materials. Process industries are a pivotal part of many value chains. Their presence on European territory strengthens the independence and resilience of our society to unexpected events or crises as it guarantees access to essential products and services to European citizens. Being large energy and resources consumers, the process industries are by the same token key to enable a climate neutral energy system and to contribute to a circular economy.

The Processes4Planet (P4Planet) partnership is about **transforming European process industries to make them circular and achieve overall climate neutrality at EU level by 2050, while enhancing their global competitiveness.**

**The systemic shift required to transition to a climate neutral and circular society calls not only for technological innovation, but rather for a holistic systemic socio-economic approach.** This is the spirit of the Processes4Planet (**P4Planet**) 2050 roadmap. The change is needed on many levels from various actors. This roadmap outlines the transformations through which the process industry can contribute and the connections along the value chains that are fundamental to enable these transformations.

More specifically, the P4Planet partnership will aim at achieving **3 general objectives**:

1. **Developing and deploying climate neutral solutions:** P4Planet ambitions to contribute to the climate neutrality of the overall European economy by bringing technological and non-technological innovations to readiness for subsequent deployment.

Today the process industries supporting P4Planet emit about 749 million tonnes of CO<sub>2</sub> annually<sup>3</sup>. To contribute to the overall climate neutrality at EU level by 2050, the process industries will redesign industrial processes and rethink their interaction with the energy system (sector coupling).

2. **Closing the energy and feedstock loops:** process industries will develop and deploy sustainable circular business models through technological and non-technological innovations, cross-sectoral collaboration and engagement with the local ecosystem. This will help them evolve towards resource circularity and resource efficiency. P4Planet ambitions near zero landfilling and near zero water discharge in 2050.

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<sup>2</sup> A definition for climate neutrality can include emissions and removals of all GHGs across the entire value chain as well as other climate impacts and may consider the remaining carbon budget. This roadmap focuses on deep CO<sub>2</sub> emissions reductions in the process industry in 2050.

<sup>3</sup> This includes direct emissions as well as indirect emissions from electricity consumption

Secondary resources (i.e. recycled materials that are transferred back to the production of new materials and goods) today contribute for 12% of the total material demand in the EU<sup>4</sup>. Recycling all materials and valorising all waste streams by 2050 implies a fundamental redesign of value chains. Industries need to establish new collaborations, e.g. with the waste management industry and with municipalities to realise a paradigm shift and become fully circular with full focus on upcycling.

- 3. Achieving a global leadership in climate neutral and circular solutions, accelerating innovation and unlocking public and private investment:** innovation is needed to make climate neutral and circular solutions more attractive. The competitive position of the European process industries will benefit from a global leadership in these economically attractive solutions, as well as from a strengthened integration in the economic fabric of regions and Member States.

The partnership will define a reliable investment agenda for process industries over next 30 years, in particular for the key phase for commercial deployment of sustainable technologies by 2030 (i.e. between 2025 and 2030). It will also address the required framework conditions to generate a market for climate neutral and circular solutions and to trigger deployment of innovation (consistent regulatory framework, level playing field).

**Many challenges common to several sectors can be addressed through cross-sectorial collaboration**, e.g. achieving high temperatures using electricity or sharing information in the value chain. The effectiveness and efficiency of innovation programmes can be increased by developing such innovations jointly and sharing learnings. Additionally, cross-sectorial innovation offers the advantage of faster deployment and impact at scale. SPIRE has already shown the effectiveness of its unique cross-sectorial innovation approach under Horizon 2020; P4Planet aims to find still more synergies in cross-sectorial innovation in the coming period. P4Planet will connect to other initiatives that develop sector-specific (e.g. Clean Steel) or solution-specific (e.g. Hydrogen Europe or CBE) innovation for the process industries.

**In this roadmap, the A.SPIRE community outlines the innovation needed to enable climate neutral, circular and competitive process industries in 2050.** In the period 2018-2020 the A.SPIRE community has worked together to develop this roadmap with regular interaction with the European Commission and other stakeholders. It presents its vision for circular and climate neutral process industries and details the innovation needed to realize this vision. Figure 1 schematically depicts the resource and energy flows of the process industries in 2050. For clarity, resources and energy are depicted separately but they are in fact interlinked. There is no silver bullet: multiple options need to be developed that can each be most effective and efficient in different applications and/or regional circumstances. The roadmap contains innovation in resources and energy, accelerated by digitalisation and Hubs for Circularity:

- On the **resources** side, the recycling of all materials will be enabled by developing industrial processes, sorting/separating technologies, and circular value chains that leverage industrial-urban symbiosis models. The innovations will boost resource efficiency and enable the valorisation of all by-products (through novel applications and industrial-urban symbiosis). This will reduce EU dependency on imported feedstock including critical raw materials and will reduce the associated environmental pollution. CO<sub>2</sub> capture, purification and utilisation will be developed for minerals, chemicals and

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<sup>4</sup> on average only 12% of material resources used in the EU in 2016 came from recycled products and recovered materials - thus saving extraction of primary raw materials. This indicator, called circular material use rate, measures the contribution of recycled materials to overall demand (EUROSTAT 39/2019, "Record recycling rates and use of recycled materials in the EU").

fuels. Non-technological innovation is needed to address barriers for the closing of loops (e.g. social acceptance, standards, etc.).

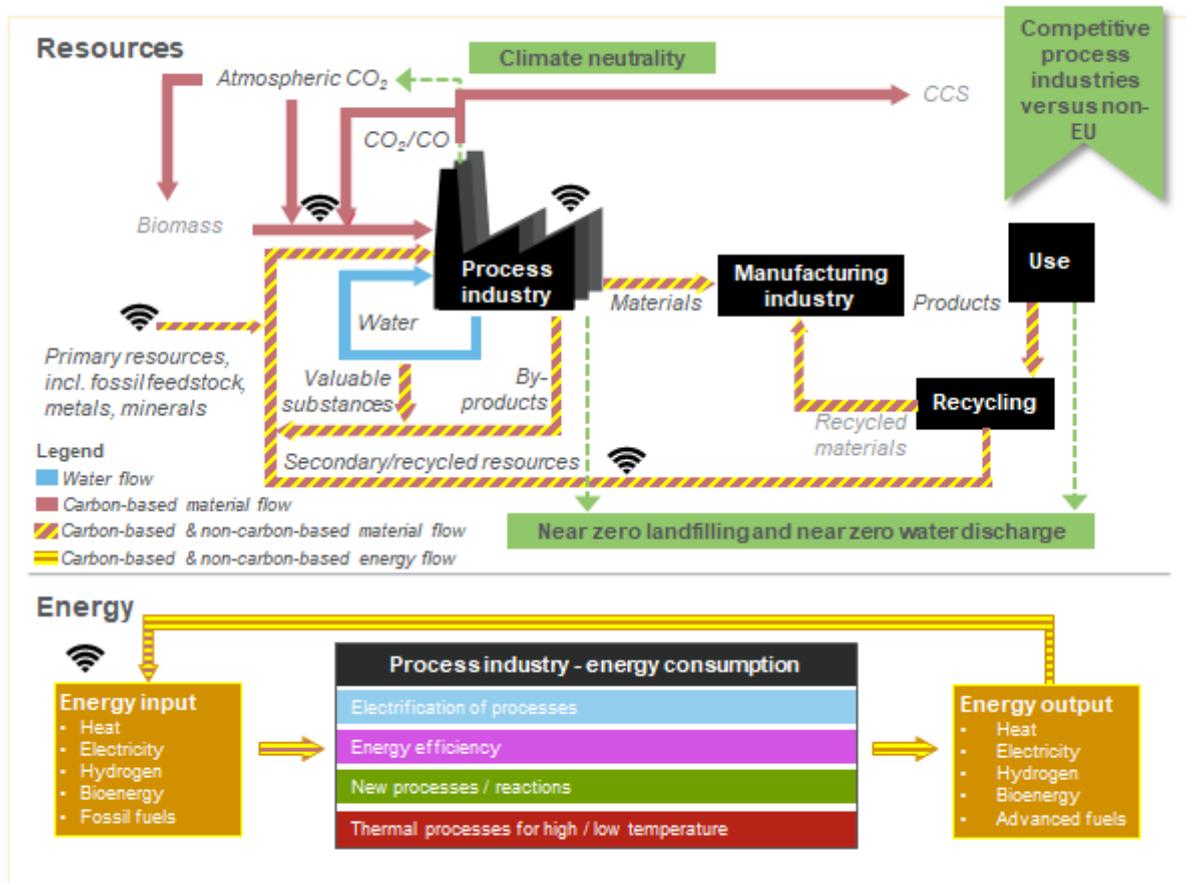


Figure 1: Resource and energy flows of the process industries in 2050

- On the **energy** side, innovation is needed for changing the energy mix, in new technologies for the integration of electricity (indirectly and directly) as well as for energy efficiency and waste energy re-use.

On top further energy use will be considered as technologies based on lower energy content feedstock might be considered. Energy efficiency (especially in new processes) and reuse of waste energy will play a significant role to improve competitiveness and reduce the need for energy (partially through existing technologies, but also by developing disruptive, more efficient processes). The use and availability of renewable electricity will drive GHG emissions from electricity consumption towards zero in 2050. Processes that require heat will be replaced as much as possible by processes that use energy to directly drive the process (avoiding the need for heat). GHG emission-free energy carriers (including renewable electricity) will be used to generate the heat for the remaining thermal processes. New energy carriers (hydrogen, ammonia and others) and renewable energy (e.g. heat or power) need to be integrated into the processes, allowing for flexibility and demand response.

- Digitalisation** will enable faster development of new solutions and speed up engineering. It will also allow for more intelligent operation of installations and enable

cross-sectorial collaboration by tracking data and sharing information in an effective and secure manner.

- **Hubs for Circularity (H4Cs)** will catalyse regional industry-society collaboration necessary to develop the solutions within the local context (and address the local barriers) by connecting various regional stakeholders. The regional dimension of the hubs will help implement the technologies and attain the ambitions of the partnership. Knowledge and best practice from regions will be shared through an EU-wide Community of Practice, and the H4Cs will be spread across Europe to deploy circular economy at scale.

**The 14 innovation areas presented in the roadmap are expected to collectively deliver these technological and non-technological solutions.** The roadmap is built up of 36 detailed innovation programmes that are clustered in distinct innovation areas. The innovation programmes push multiple technologies towards commercial application (TRL9<sup>5</sup>). About 50% of the developed technologies could be applied by 2030 and 100% by 2050. Table 1 shows the progression on innovation area level.

Innovation area	Progress up until milestone year <sup>1,2</sup>			
	2024	2030	2040	2050
Renewable energy integration				
Heat reuse				
Electrification of thermal processes				
Electrically-driven processes				
Hydrogen integration				
CO <sub>2</sub> capture for utilisation				
CO <sub>2</sub> utilisation in minerals				
CO <sub>2</sub> & CO utilisation in chemicals and fuels				
Energy and resource efficiency				
Circularity of materials				
Industrial-Urban symbiosis				
Circular regions				
Digitalisation				
Non-technological aspects				

<sup>1</sup> Progress is depicted here as % of total TRL9 projects programmed in each area, and for circular regions, digitalisation, and non-technological aspects % of total investment needs until 2050.

<sup>2</sup> It is extremely difficult to foresee future technological developments and related innovation opportunities over a 5- to 10-y horizon. This Table outlines the foreseeable progress of each innovation area based on best available knowledge about technologies under development.

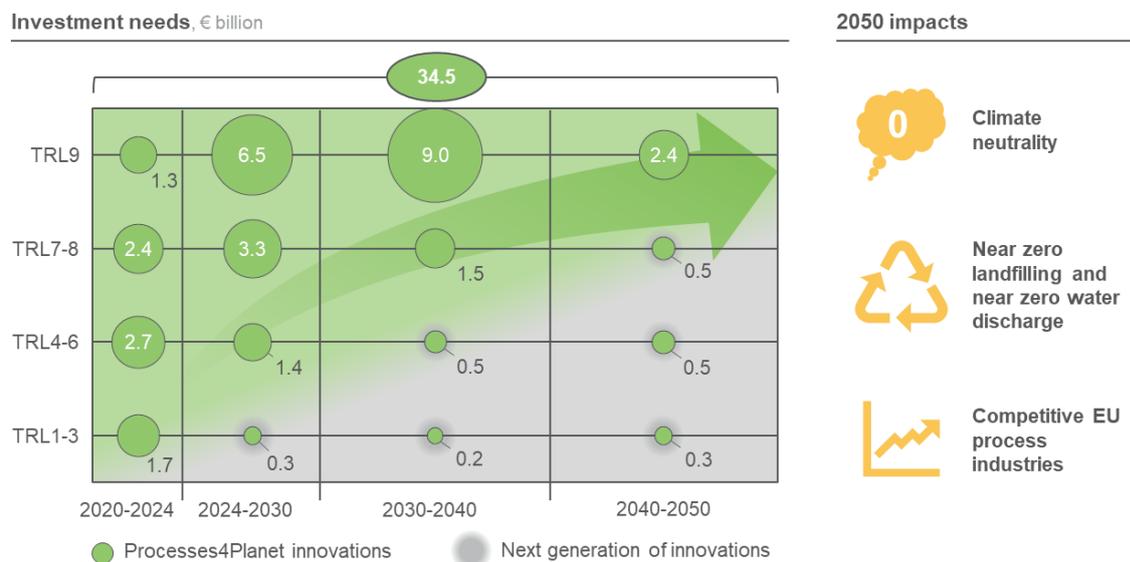
**Table 1: Progression of P4Planet innovation pipeline**

**€34.5 billion of investments are estimated to be needed until 2050 to develop and progress this highly ambitious pipeline of innovation.** This includes the total investments of

<sup>5</sup> Technology Readiness Level, see Appendix C for a definition

the projects (CAPEX for the innovative parts of installations, and OPEX for testing, including materials etc.) from TRL1 to 9, including first-of-a-kind demonstration plants. It also includes funding for non-technological activities. For the period 2020-2030 investments are estimated at €19.8 billion, of which €10.1 billion are in the expected TRL range of Horizon Europe (i.e. TRL4 to 8) and in non-technological activities.

Figure 2 depicts a more detailed breakdown of the technological investment needs. Note that estimates after 2030 are more uncertain than the estimates before 2030. The non-technological investments amount to €303 million until 2050.



**Figure 2: Investment needs for P4Planet’s innovation pipeline**

Figure 2

Besides the direct investments shown in Figure 2, indirect investments are expected (e.g. in the supply chains to produce components, transport, etc.). Massive investments in electricity production are needed to reduce its carbon intensity. For full deployment across Europe additional investments are needed that are estimated at around 1 to 3 trillion € based on the limited available information.

**A.SPIRE members have coined the term “marbles”** to describe a first-of-a-kind (FOAK) large scale application of one or more new technologies, integrated in its value chain, deployed by the process industry. They indicated their **intention to invest in marbles to bring them to TRL9**, confirming a market pull for the innovations and the relevance of this roadmap. The marbles demonstrate the impact of the overall P4Planet programme. The initial set of marbles identified is already covering the overall set of innovation areas and programs defined in the 2050 roadmap showing the coherence of the P4Planet roadmap with industry priorities. It will be a showcase to the society and related industries that the demonstrated new technological concepts are technically and economically feasible and leads to the expected impact at the level of climate neutrality and/or circularity.

**A supportive policy framework is essential for rapid deployment in European process industries.** Deployment requires a market demand for the developed innovations. Governments can play a role in stimulating market creation. Recycling policies should incentivize higher-value applications for secondary materials and remove hurdles for (cross-border) recycling. A suitable policy environment should be put in place for the use of CO<sub>2</sub> as a feedstock.

**The transformation will not succeed without large quantities of cost-competitive GHG emission-free energy** as demand will surge in the process industries (as well as other sectors).

Besides the energy itself, energy transport infrastructure (e.g. increased electricity grid capacity and hydrogen transportation infrastructure) should also be built on time. Additional infrastructure is required for waste collection and sorting and for CO<sub>2</sub> transportation.

**P4Planet is well-positioned to make this roadmap come true.** P4Planet will translate the innovation programmes in this roadmap into a pipeline of projects with high positive impact. It will adopt a holistic perspective based on needs from industry, society and other stakeholders, such as international organisations. P4Planet will disseminate knowledge effectively to accelerate development and deployment, partly through the European community of practice. By collaborating with other partnerships, initiatives, innovation funds and financing schemes, P4Planet will align efforts between the process industry, its various value chains and the energy sector to avoid duplication of efforts and ensure a smooth, coordinated and efficient delivery of the transition towards a climate neutral and circular society.

## 2 A 2050 vision for European process industries

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*Imagine our continent in 2050: Europe is climate neutral and has a highly circular economy. Products that once ended up in landfills are now recycled to become feedstocks for the process industries. People enjoy living in clean cities, and regions thrive on the many jobs and economic value created from higher resource efficiency. Different regions in Europe use different sustainable models to prosper without harming the environment. Technologies developed in Europe by and for the process industries over the past decades are being exported, boosting the European economy and maximising the global environmental benefits.*

*To get there, the process industries have seen an unprecedented rate of change after 2020. Through research and innovation, existing processes have been significantly optimised, and new and disruptive processes have been developed and implemented, supported by uniform European regulations. The new processes, and associated deployment of vast renewable energy and hydrogen production and transportation infrastructure, enabled the process industries to drastically improve their environmental footprint and to help realise a climate neutral society.*

### 2.1 Towards a climate neutral and circular Europe

**Climate change is one of the preeminent issues of our time.** The 2015 Paris agreement defined the global climate ambition to limit the global temperature increase to well below 2 °C (and to pursue efforts to limit temperature increase to 1.5 °C) above pre-industrial levels.

The **European Green Deal** (European Commission, 2019)<sup>[1]</sup> is a game changer for our society at large, and for the European process industries in particular. It launches a new growth strategy that aims to transform the EU into a fair and prosperous society, improving the quality of life of current and future generations, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use. The European Green Deal reaffirms the Commission's ambition to make Europe the first climate-neutral continent by 2050.

As part of the EU Green Deal legislative package, the « **European Climate Law** »<sup>[2]</sup> enshrines the EU 2050 climate-neutrality objective in legislation: the EU's greenhouse gas emission reduction target for 2030 is increased to at least 55% compared with 1990 levels, including emissions and removals<sup>[3]</sup>.

This European pledge combined with pledges which have been or are still to be made by other countries, should collectively ensure that our world remains under 2°C of temperature increase. A just distribution of the mitigation efforts between all regions and countries should also create a level-playing field which should help maintain the European competitiveness.

The **New Circular Economy Action Plan for a Cleaner and more Competitive Europe**<sup>[4]</sup> outlines the upcoming EU initiatives to achieve its circular economy ambitions. A circular economy will contribute significantly to the GHG targets and has other major strategic benefits : less resource dependency, minimised resource depletion, increase in jobs and social integration and cohesion, etc. The Action Plan underlines the crucial role of innovation : « Horizon Europe will support the development of indicators and data, novel materials and products, substitution and elimination of hazardous substances based on “safe by design” approach, circular business models, and new production and recycling technologies, including exploring the potential of chemical recycling, keeping in mind the role of digital tools to achieve circular objectives. ». Circularity is also about removing components which could harm human health and/or the environment from successive material cycles.

In order to achieve these various objectives, **an unprecedented transformation of production and consumption practices must be deployed at scale over less than 30 years.**

The recently released “**New Industrial Strategy for Europe**”<sup>[5]</sup> is very clear in its ambition and in the recommended way forward:

- “Energy-intensive industries are indispensable to Europe’s economy and are relied on by other sectors. Modernising and decarbonising<sup>[6]</sup> energy-intensive industries must therefore be a top priority”.
- “Industrial sectors should be invited and incentivised to define their own roadmaps for climate neutrality or digital leadership. These should be enabled by high quality research and skills and supported by the EU. In the co-design and entrepreneurial spirit of this strategy, this should be supported through Public Private Partnerships to help industry develop the technologies to meet their goals, as has successfully been done in industrial alliances”.

**The P4Planet Partnership is the answer to this call for action.** It will be an essential tool to deliver the innovations we need, building on the achievements of SPIRE (the European contractual public-private partnership which aims to enhance resource and energy efficiency in the process industries) but representing a paradigm shift as it greatly raises the level of ambition by embracing the transformational objectives of the European Union: climate neutrality, circularity, competitiveness.

The P4Planet Partnership is about **transforming European process industries to make them circular and achieve overall climate neutrality at EU level by 2050, while enhancing their global competitiveness.**

It will aim at achieving **3 general objectives**:

1. **Developing and deploying climate neutral solutions:** the transition to climate neutrality can only be achieved if technological and non-technological carbon neutrality innovations are brought to readiness for subsequent deployment.
2. **Closing the energy and feedstock loops:** through technological and non-technological innovations, cross-sectoral collaboration and engagement with the local ecosystem, process industries will develop and deploy sustainable circular business models and will move towards resource circularity and resource efficiency.
3. **Achieving a global leadership in climate neutral and circular solutions, accelerating innovation and unlocking public and private investment:** the competitive position of the European process industries will be enhanced by a strong positioning as global leaders in economically attractive solutions for climate-neutrality and a fully circular economy and a strengthened integration in the economic fabric of regions and Member States. The partnership will define a reliable investment agenda for process industries over next 30 years, in particular for the key phase for commercial deployment of sustainable technologies by 2030 (i.e. between 2025 and 2030). It will also address the required framework conditions to generate a market for climate neutral and circular solutions and to trigger deployment of innovation (consistent regulatory framework, level playing field).

<sup>[1]</sup> COM (2019) 640, The European Green Deal, 11 December 2019

<sup>[2]</sup> Regulation of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999

<sup>[3]</sup> Compared to a 40% reduction target by 2030 in the “2030 Climate and Energy Framework” released in 2014 (Communication from the Commission, A policy framework for climate and energy in the period from 2020 to 2030, COM/2014/015 final).

<sup>[4]</sup> COM(2020) 98 final, A New Circular Action Plan for a cleaner and more competitive Europe, 11 March 2020

<sup>[5]</sup> Communication from the Commission, A New Industrial Strategy for Europe, COM (2020) 102 final.

<sup>[6]</sup> The wording of “decarbonisation” cannot strictly be applied to the chemical industry, as nearly all chemicals contain carbon or are made using carbon (notably organic chemistry compounds and the reduction of ores). In

this document, we will give preference to the wording “transition to climate neutrality” which is relevant for all process industry sectors.

## 2.2 The important role of process industries

**Process industries produce the materials that are used by the manufacturing industry to make products.** Materials like cement, steel, plastics, paper, industrial minerals, chemicals and ceramics are created from raw material resources (e.g. iron ore, minerals, wood, oil or gas) in energy-intensive processes. Some materials are the first step of a long value chain (e.g. a chemical that is used in a plastic that is used in a component that is used in a car) and other materials are directly used as a product (e.g. roof tiles, transport fuels).

**The transformation of the process industries is key as they are energy intensive.** The energy sector will undergo a massive disruption in the coming decades to decrease its GHG emissions, and this will affect all value chain stakeholders. Process industries account for a significant part of energy consumption and therefore will be an important part of this ecosystem. Process industries will need to cooperate and align with the energy sector to make optimal use of alternative energy resources/feedstocks and contribute to the transition. Process industries are essential to accelerate the energy transition, as they can offtake large volumes of GHG emission-free energy and thereby rapidly decrease production costs to a competitive level. Additionally, due to their high energy consumption, process industries can contribute significantly to system flexibility by shifting energy demand, thereby enabling a GHG emission-free, highly digitalised, and dynamic energy system.

**At the same time, process industries can close material loops while minimising/removing substances of concern for human health and the environment in recycled materials and products.** A circular economy is only possible with the process industries, given their pivotal importance in the most critical value chains. In the transition towards more recycled, CO<sub>2</sub>-based and bio-based materials, the process industries play an important role as they can use these materials to replace primary resources.

## 2.3 Shifting value chains

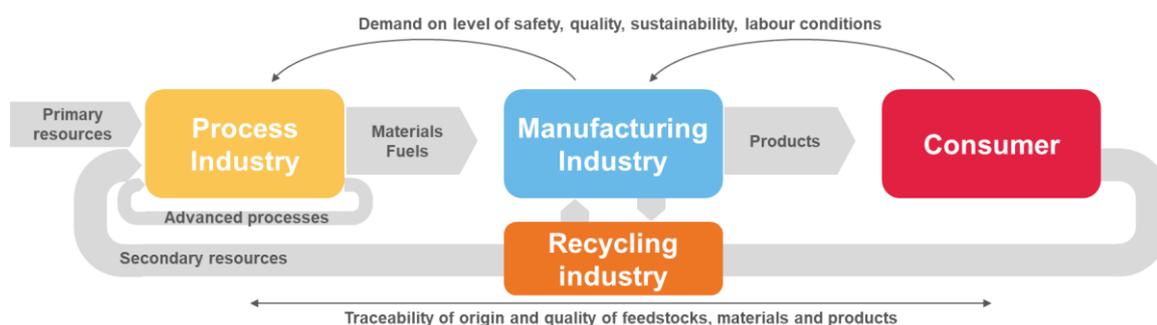
**Consumers increasingly demand guaranteed quality, safety, performance, and sustainability** (e.g. labour, environmental and climate impacts) of the products they buy and of the materials used to make these products. Additionally, consumers are increasingly requiring customised products, and changing consumer behaviour (for example sharing models) is disrupting value chains and business models. Product manufacturers and brand owners are increasingly sensitive to the demands of their customers and are rethinking product design across the entire value chain in response to society and regulatory demands. The origin of materials and the way they are processed have become a major concern for brand owners.

**Evolving value chains and business models will meet new consumer demands.** Value chains will become circular and more complex, connected and intertwined. In response, process industries will develop new activities, or cooperate (more) with existing players along the value chain, both upstream (e.g. recycling) and downstream (e.g. materials-as-a-service models).

**The process industries will improve the overall environmental footprint of products along the whole value chain through innovating their processes and materials.** Process innovation will focus on developing disruptive new processes and improving existing processes to decrease the environmental footprint of materials, minimize pollution and evolve towards a

toxic-free environment. New and innovative materials<sup>6</sup> designed for a circular and climate neutral economy can contribute to sustainability and circularity in many ways, including a higher inherent recyclability.

**Process industries will become a more integrated part of an evolving circular value chain** (see Figure 3). 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, boosting the value added by the process industries. On the other hand, process industries will work more closely with brand owners and service providers downstream to ensure that the materials developed by the process industries will be apt for the circular economy without compromising on performance. In the case of fuels, produced by refining, these are products going immediately to the consumer.



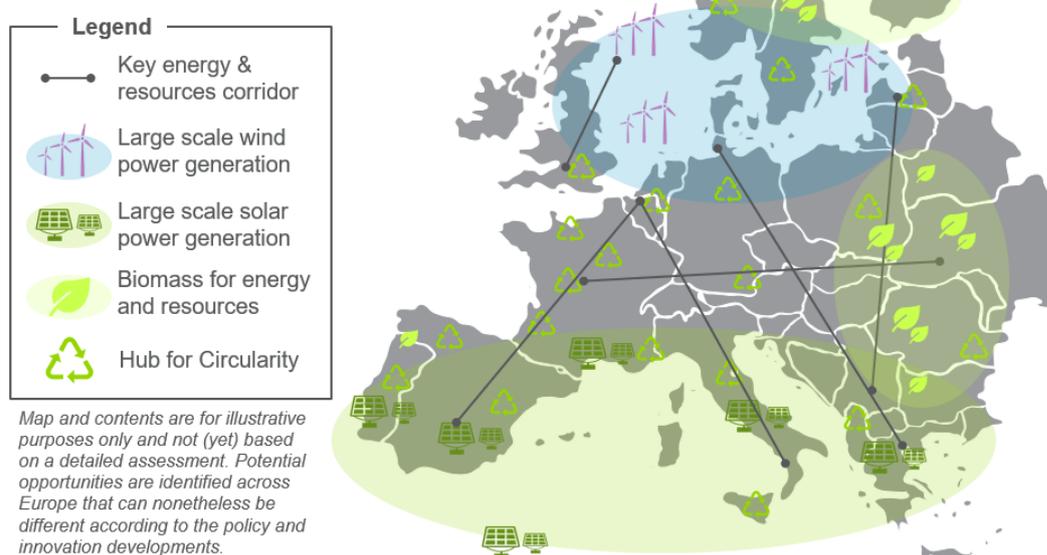
**Figure 3: The process industries will have an important, more integrated role in new circular and more sustainable value chains, working closely with manufacturing and recycling sectors**

**New central and decentral energy value chains are paramount to process industries transformation.** The energy system in a climate neutral Europe will shift away from fossil fuels and fossil feedstocks, and renewable energy as well as renewable feedstocks will play a major role in energy supply (EC, 2018).

The paradigm in the management of the power system is changing from supply side to demand side management of the grid, with a large buffer of energy storage. This calls on the process industries to regulate their electricity demand. The process industries will be more integrated in energy value chains to deliver this: producing new fuels (hydrogen, ammonia, methanol and others), anticipating power supply and other interactions. Figure 4 illustrates how the process industry can play a key role in achieving synergies in the European energy and materials systems.

<sup>6</sup> Materials produced by the process industry, enabling production of downstream products with improved functionality. Note that downstream products as such are not part of the P4Planet focus.

**Process industries play a key role in a carbon neutral and fully circular European economy in 2050**



**Figure 4: EU Process Industries achieve synergies locally tailored to regional conditions (locations of the H4Cs are illustrative only – these have not yet been determined).**

## 2.4 Competitive European process industries

**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. Currently the process industries provide about 8.5 million jobs directly and 20 million indirectly. Process industries continuously attract talent and incite academia to train the next generation of experts. Process industries have a turnover of € 2 trillion/year, drive innovation, and develop solutions for societal problems.

**Focused innovation efforts will transform the European process industries.** The process industries will adapt 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.

**As many process industries compete on a global playing field, the competitiveness of these industries needs to be safeguarded throughout the transition.** The transformation of EU process industries requires unprecedented levels of investments. If new technologies come

at higher cost, there is a risk that European process industries lose their competitiveness. This needs to be avoided through an effective policy framework, but competitiveness can also be boosted by innovation and scale (e.g. driving down cost of process technologies or of inputs).

## 2.5 P4Planet objectives and ambitions for the 2050 process industries

**Innovation will enable the European process industries to keep playing a pivotal role in the transition towards a prosperous, climate neutral, and circular European society.**

P4Planet is committed to deliver the necessary technological and non-technological innovations.

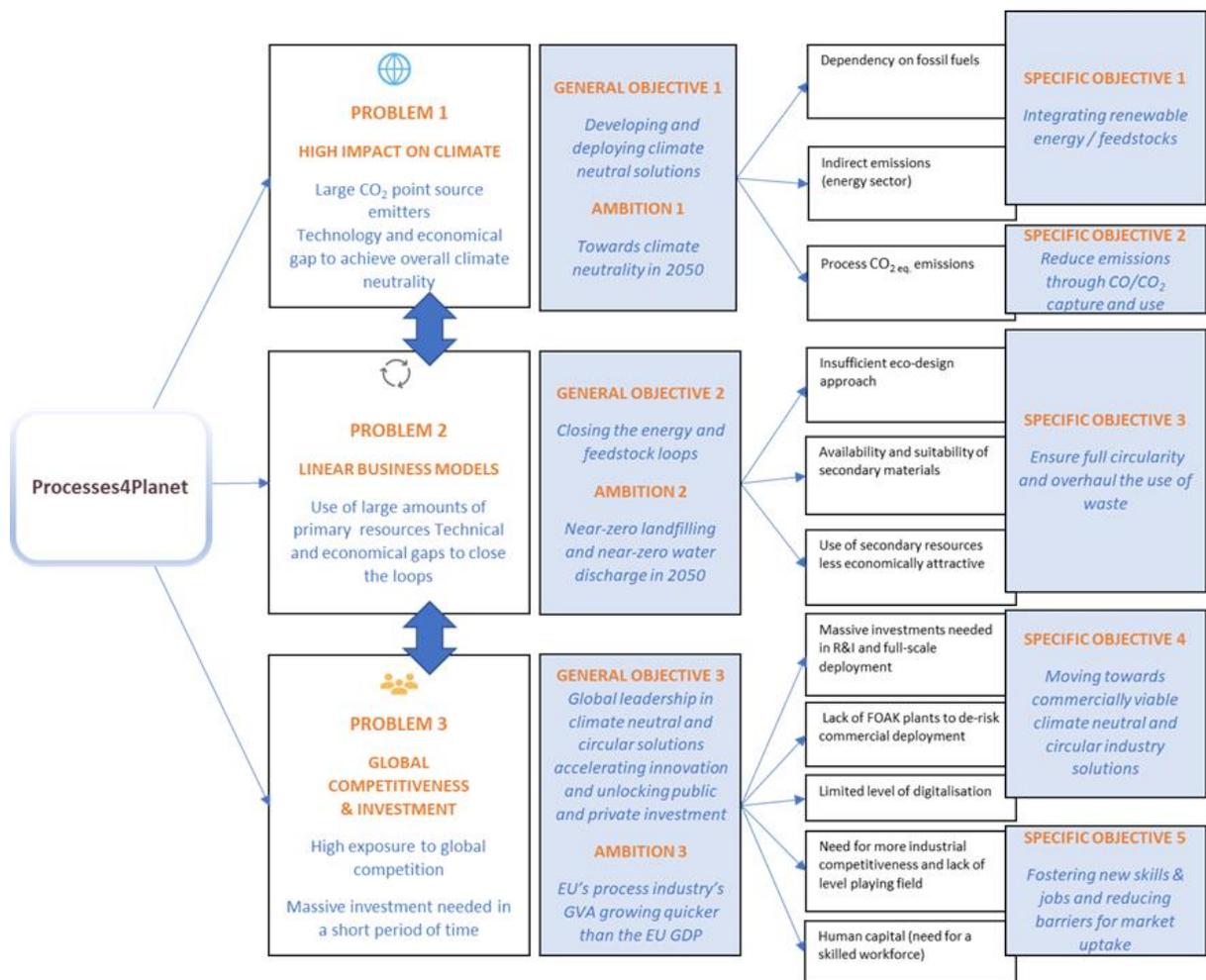
As extensively explained in the P4Planet Guidance Document, Processes4Planet addresses **three interlinked problems that are specific to the process industries:**

- **High impact on climate:** process industries are today large CO<sub>2</sub> point source emitters and face major technology and economical gaps to achieve the 2050 target of overall climate neutrality;
- **Linear business models:** process industries use large amounts of primary material and energy resources; closing the material loops is not in many cases yet technically and/or economically feasible at scale;
- **Global competition and level of investment:** European process industries are highly exposed to global competition. Massive investments are needed in a very short period of time (compared to traditional investment cycles of process industries).

For each of these 3 key problems, a **General Objective** (qualitative/semi-quantitative) and an **Ambition** (quantitative target) were defined.

Similarly, at a more granular level, P4Planet's **specific objectives** were adopted to address one or several of the problem drivers which are today at the source of the 3 identified critical problems.

Figure 5 presents the 3 key problems, the general objectives and ambitions as well as the specific objectives of the partnership (addressing one or several problem drivers).



**Figure 5: the 3 key problems, the general objectives and ambitions as well as the specific objectives of the partnership (addressing one or several problem drivers)**

More explanations are given below for each of the 3 P4Planet's ambitions.

### Climate Neutrality

#### *Towards climate neutrality in 2050*

*Process industries as frontrunners in a transition which sustains quality of life for all*

The process industries are critical to **deliver on ambitious climate objectives** while sustaining (and wherever possible) enhancing quality of life for all citizens.

Reaching the European climate ambitions will not be feasible without the disruptive transition of the process industries that P4Planet aims to foster, as they are today a significant contributor to greenhouse gas emissions. Process industries will also be, due to the extent of their energy consumption, a critical enabler for a fast, large scale and **cost competitive** deployment of climate-neutral energy and energy carriers (for instance green hydrogen) in Europe. They can also contribute to smoothing out grid fluctuations resulting from the integration of renewables.

The innovative process technologies developed by Processes4Planet supported by an appropriate regulatory and investment framework will

	<p>enable an economically competitive production of climate-neutral products, that will be needed to sustain the delivery of day-to-day services enhancing the quality of life of citizens.</p>
<p><b>Circularity Resources</b></p> <p><i>Near-zero landfilling and near-zero water discharge in 2050</i></p>	<p><i>Closing the loops of water reuse and from waste to resources</i></p> <p>Our society must achieve a <b>paradigm shift in the way resources are being managed and used</b>. Waste generation must be minimised beginning with the design stage of materials and products. Disposal of re-usable wastes must disappear as waste flows from municipalities and industries are collected better, sorted better and processed in an innovative way to fulfil the specifications of resources needed for the production of new marketable materials and goods. The use of captured CO<sub>2</sub> and an effective management of water resources are also essential components of the circular business models of the future.</p> <p>It is also crucial to move towards toxic-free material cycles and clean recycling by ensuring that substances of concern in products and recycled materials are minimised<sup>7</sup>.</p> <p>The Process Industries are again crucial to deploy a circular economy at scale and to deliver on EU ambitions in this area due to their resource- and energy-intensive nature. They can only achieve this change if robust and novel collaboration models are permanently established across industrial sectors, across value chains and with regions, living labs, municipalities and citizens in addition to the technology developments required.</p>
<p><b>Competitive Process Industries</b></p> <p><i>The innovations contribute to the EU's process industry's GVA grows quicker than the EU GDP</i></p>	<p><i>A thriving industry providing quality jobs for all industry workers</i></p> <p>Innovative process technologies are essential to sustain the competitiveness of European process industries in their transition towards fully sustainable business models. Flourishing process industries support (new) skills development and provides (new) quality jobs for industry workers at all qualification levels in Europe. An industry leading in technological innovation can efficiently deploy sustainable processes around the world, contributing to the achievement of global emissions reduction objectives.</p>

**The extent and the pace of the transformation are pushing the limits of human knowledge and our ability to deploy innovations.** Three decades remain to achieve the transformation, but many production assets have lifetimes of 20 to 50 years or more. This means that there is a risk for lock-in if technologies are not yet available at the time of re-investments. To avoid this lock-in, technological development should happen as quickly as possible. Integration of process industries within the new value chains and a low-carbon energy system poses additional

<sup>7</sup> COM(2020) 667 final Chemicals Strategy for Sustainability Towards a Toxic-Free Environment

challenges. The changes to the sites, infrastructure, value chains and business models may take decades, so it is key to accelerate as much as possible, starting now.

**Digitalisation and regional hubs for circularity will serve as accelerators for the transformation.** Digitalisation will enable the fast development of new materials and processes and of industrial-urban symbiosis and make a major contribution to improving the energy and resource efficiency of plants and value chains. To strengthen their global competitiveness in a turbulent economic environment and the transition into a climate neutral and zero-waste economy, process industries must reap the full benefits of what digital technologies have to offer today. Hubs for circularity (H4C) bring together local stakeholders to jointly find regional synergies and accelerate the transition by implementing technologies. These hubs can address the local non-technological barriers and meet local societal needs to make sure that the technological innovations gain societal awareness and acceptance.

Figure 6 summarises P4Planet’s vision of how to achieve the required transformation of process industries. Industrial-urban symbiosis, process innovation, digitalisation and non-technological aspects are key to transform the process industries. Process innovation includes innovation in the fields of electrification, energy mix and hydrogen, capture and use of CO<sub>2</sub> and CO, and resource flexibility. Industrial symbiosis, digitalisation and the non-technological aspects (e.g. new business models) support and accelerate the transformation and embed the redesigned process industries in a circular and climate neutral society.

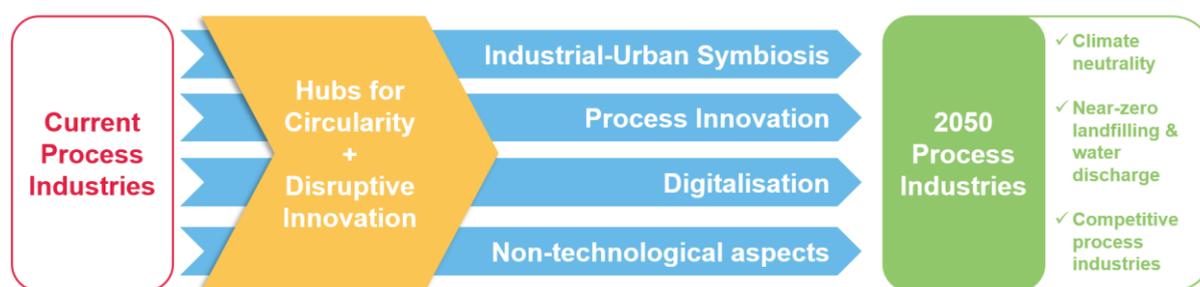


Figure 6: How P4Planet will achieve its ambitions<sup>8</sup>

## 2.6 How to read this roadmap

The next chapter explains the need for cross-sectorial innovation. It presents the current status of the process industries concerning GHG emissions and waste, explains the innovation needs to meet the ambitions and describes how these relate to the various sectors. Chapter 3 also details the concept of H4C and describes how P4Planet fits in the EU innovation landscape.

Chapter 4 presents how P4Planet aims to deliver the required innovation. 14 innovation areas are presented, and the chapter explains how the innovation programmes in each area interrelate and enable each other. In Appendix A the 36 innovation programmes are further detailed.

Chapter 5 synthesizes the innovation programmes. It presents the impacts from the innovation programmes towards meeting the three ambitions, the key milestones of the roadmap and the investments that are needed to realize the portfolio of innovations. Furthermore, it stresses the benefits of P4Planet and define the boundary conditions for the roadmap’s success.

<sup>8</sup> A definition for climate neutrality can include emissions and removals of all GHGs across the entire value chain as well as other climate impacts and may consider the remaining carbon budget. This roadmap focuses on deep CO<sub>2</sub> emissions reductions in the process industry in 2050.

### 3 The need for cross-sectorial innovation

This chapter describes the landscape in which the Processes4Planet (P4Planet) sectors operate and shows the rationale for the cross-sectorial approach to innovation. Section 3.1 explores the challenge of the P4Planet sectors in the context of climate change and waste. This forms the basis for the innovation needs, described in Section 3.2 in general terms. The sector-specific innovation needs are presented in Section 3.3 for all P4Planet sectors. Section 3.4 focusses on the cross-sectorial dimension by introducing the Hubs for Circularity. Finally, Section 3.5 describes how P4Planet interacts with other stakeholders in the EU innovation landscape.

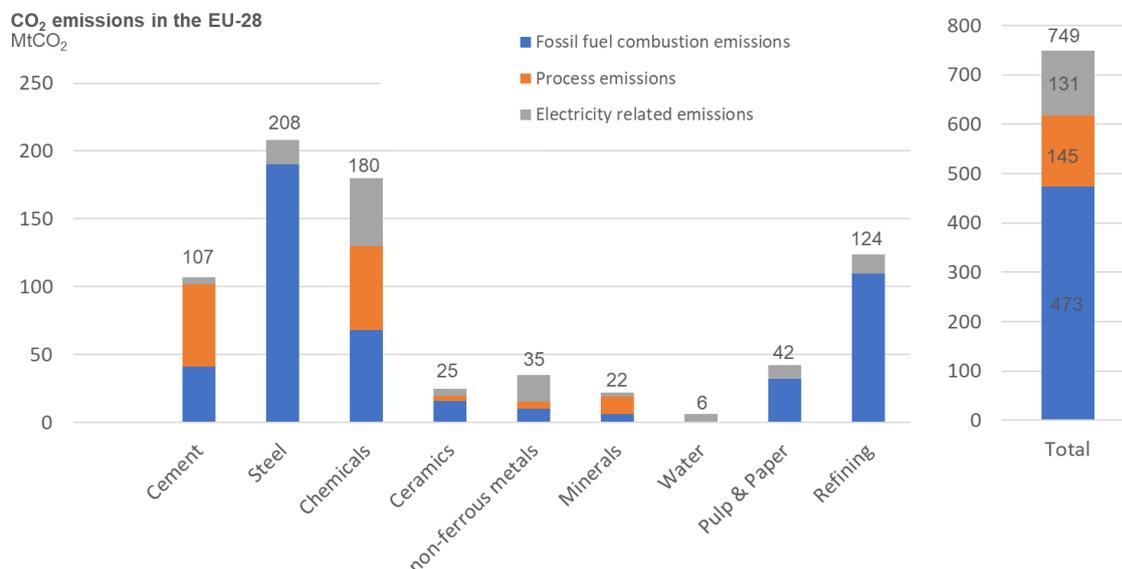
#### 3.1 The status quo of P4Planet sectors

This section explores the current position of the P4Planet sectors related to GHG emissions and waste and highlights the overarching challenges.

##### 3.1.1 Greenhouse gas emissions

This roadmap focuses on CO<sub>2</sub> as this is the predominant GHG. Other GHG emissions (such as CH<sub>4</sub> and N<sub>2</sub>O) are considered sector-specific and have therefore not been considered within the scope of this roadmap.

The P4Planet sectors collectively account for around 473 MtCO<sub>2</sub> of direct emissions<sup>9</sup> in the EU, 145 MtCO<sub>2</sub> of process emissions and 131 MtCO<sub>2</sub> of emissions from purchased electricity (see Figure 7). Together, these 749 MtCO<sub>2</sub> equate to about 17.3% of total EU emissions (i.e. 4,333 MtCO<sub>2</sub>) (EEA, 2019). Direct emissions are related to fossil fuel combustion, process emissions are directly related to the process. It must be mentioned that e.g. the chemical industry is a combination of thousands of processes of which a few as ammonia & ethylene production are responsible for relative high CO<sub>2</sub> emissions.



**Figure 7: Breakdown of current direct and electricity CO<sub>2</sub> emissions of the P4Planet sectors**

<sup>9</sup> Emission figures in this report always refer to emissions per year, unless stated otherwise

The accounting of GHG emissions of industrial sectors can be complex and different boundaries are taken to calculate sector emissions depending on the purpose of the analysis. For example, self-generated electricity can be considered part of the industrial sector or part of the power sector. For this reason, statistics from different sources differ. In the numbers presented here, data from the sector associations is used to the extent possible, and complemented with data from Eurostat and EEA, as well as other studies if needed. Feedstock-related emissions are included in fossil fuel combustion emissions in this overview. Electricity-related emissions are calculated using electricity consumption and the EU grid average emissions per kWh. The detailed approach is presented in Appendix E .

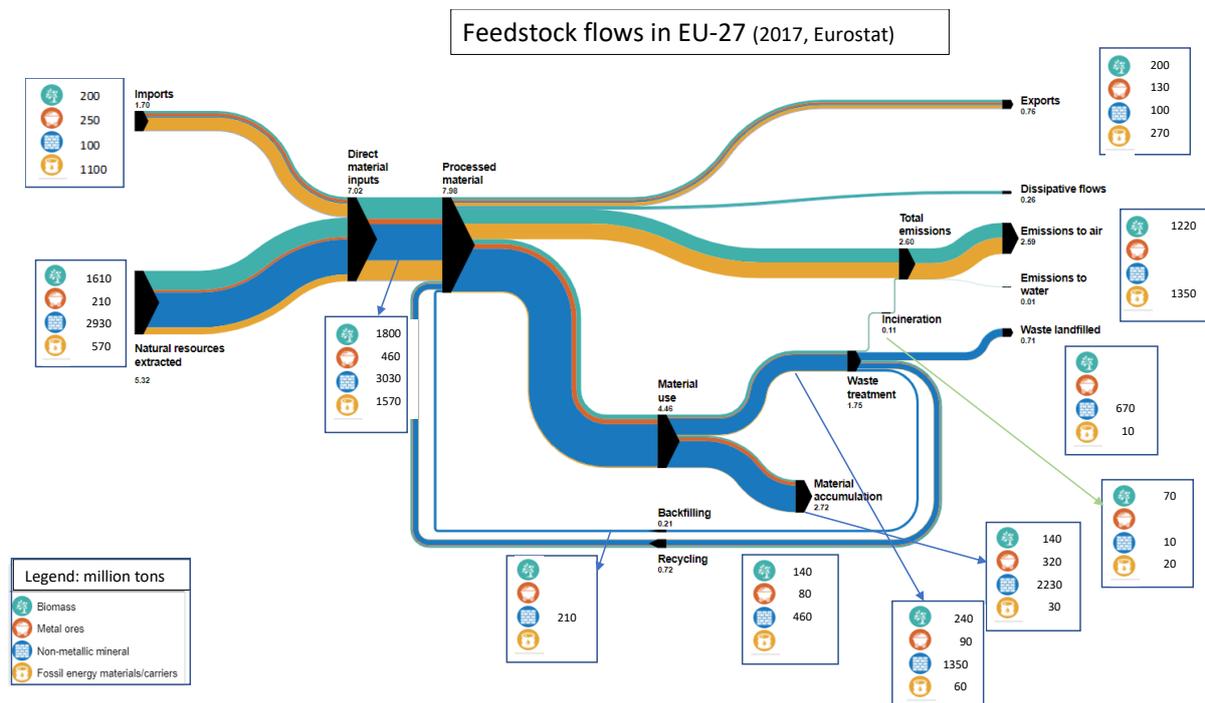
Besides the direct emissions and emissions from electricity generation, the process industries have an important downstream GHG emissions impact. For example, emissions may arise from downstream processing, or from end-of-life treatment. On the other hand, products made from materials of the process industry can also avoid emissions downstream. For example, plastic foams used as insulation material in buildings can reduce energy consumption and associated emissions. The replacement of fossil feedstocks by alternative solutions (e.g. bio-origin or CO<sub>2</sub>) could have a significant impact on reducing emissions in the transport sector.

### 3.1.2 Waste

Figure 8a represent the materials flows of the P4Planet feedstocks in general in EU-27 with attention to recycling, incineration, landfilling, etc.

Figure 8b represents the total amount of waste generated by process industries, by category.

Figure 8c gives an overview of waste streams (annually generated in the EU) with potential of re-use, recycling, recovery in the process industries.



**Figure 8a: Material flows of the largest P4Planet feedstock flows in the EU-27**

**DATA TO BE COLLECTED**

Figure 8a: Waste generation in the EU-27 by the process industries

## DATA TO BE COLLECTED

### Figure 8b: waste streams with potential of re-use, recycling, recovery by the process industries

The quality is limited (in level of detail) and gathering waste-data is difficult due to differences in definitions between Member States and different statistical systems. Furthermore, only waste that is collected is monitored and waste that is sent to recyclers is classified as “recovery-recycling”, even when a part of waste sent to recyclers would be landfilled after processing.

A significant part of the waste is currently landfilled, and another significant part is incinerated. 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) (EC, 2020).

Overall around 55% of all waste excluding major mineral waste was recycled (Eurostat, 2019a). Only 12% of the resources used in the EU in 2016 came from materials recovered and upcycled, reducing the need for extraction of primary raw material.

## 3.2 Innovation needs

Figure 9 sketches a picture of how the process industries 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. The top part of the figure depicts how the process industries fit into circular value chains (the process industries deliver materials or fuels to the manufacturing industry, which produces consumer products).

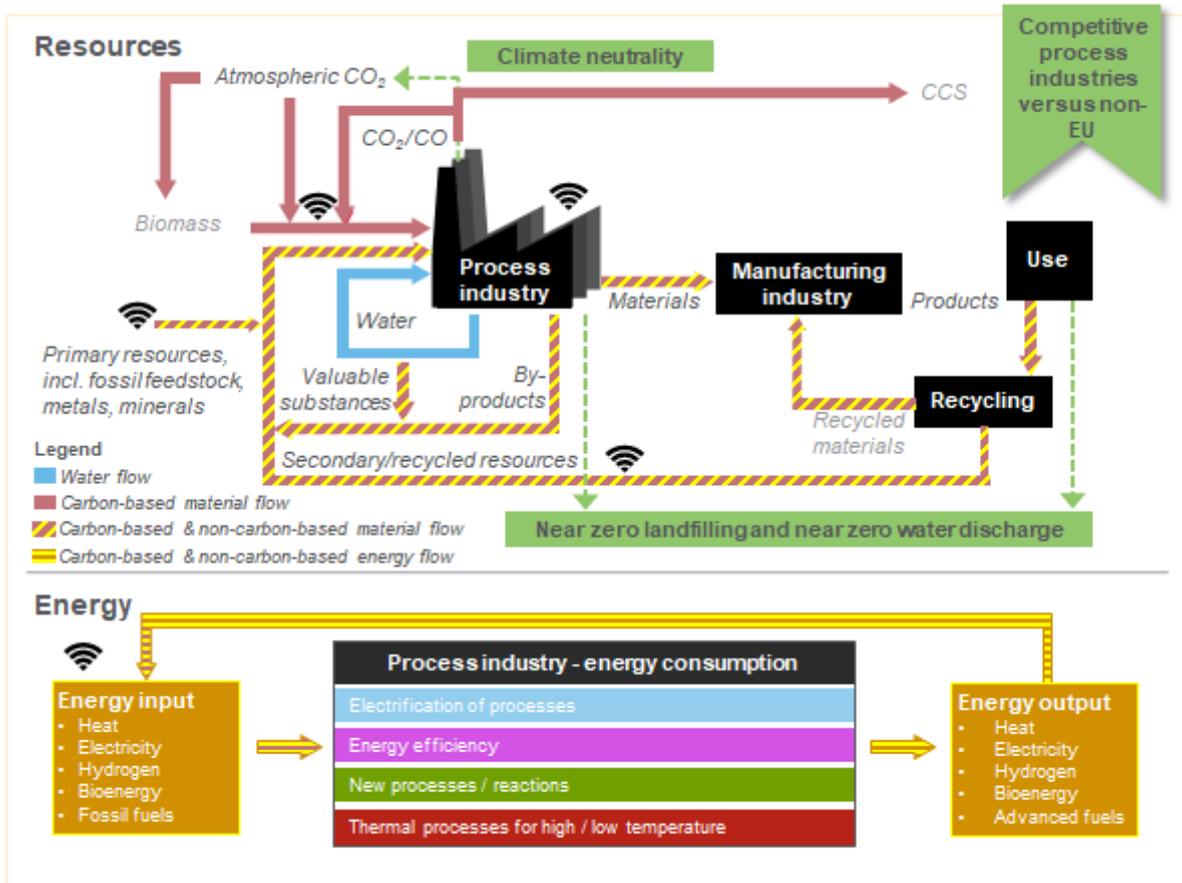


Figure 9: Visualisation of the transformation of the process industries towards zero GHG emissions and near-zero landfilling and wastewater discharge

### 3.2.1 Resources

Sectors can develop circular business models (e.g. extending product life, developing product sharing platforms, or moving from product commercialization as to service delivery) 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 basis and are only within P4Planet's scope if there are cross-sectorial elements.

#### Secondary resources

Ultimately, when the products made from the materials produced by the P4Planet sectors are at the end of their life, sectors need to cooperate with their downstream value chain(s) to optimize end of life treatment, avoiding landfilling. As Figure 9 shows, materials can be recycled to either:

- The manufacturing industry: recycling of glass, mechanical recycling of plastics, re-use of products (eventually after repair or refurbishment). The role of the process industry is limited here (although the process industry can contribute to increasing recyclability in the design of the materials they produce), and therefore the recycling technologies for these recycling routes are not in the scope of this roadmap. In other words, the repair-, refurbish-, re-use options are essentially in the hands of the manufacturing industries;
- The process industries, where waste materials are recycled (upcycled and downcycled) to be used as **secondary resources**.

### Text box 1: Recycling, upcycling and downcycling

In this roadmap, “recycling” refers to closed material loops, with the ambition to move towards toxic-free material cycles, ensuring the minimisation of substances of concern (for human health and/or the environment) and contributing thereby to the EU Green Deal zero pollution ambition

Note that where the word “recycling” is used in this roadmap it refers to upcycling (keeping a resource in the same loop, for example the recycling of aluminium with the same quality) as well as downcycling (using a material in a lower value application, for example the use of ground bricks on tennis courts). It also covers the recovery of energy from waste through their use as fuels in thermal processes (which is in some cases directly combined with material recovery/recycling), possibly after several preparation steps.

Disposal techniques and technologies (notably incineration) are not included.

As a general rule, process industries aim at upcycling waste (recycling towards high value applications) wherever possible.

This use of secondary resources in the process industries requires a local approach as there is a multitude of sectors within P4Planet, with many different processes within each sector (especially for the chemical industry) that are often collocated within industrial parks or regions.

These parks or regions have their own needs and opportunities for closing material loops. The loops can be closed locally taking advantage of short logistics, but they also can be (at least partly) interregional when critical mass or access to specific technology is required for a process to be feasible, economic and environmentally friendly. All material flows need to be sorted and separated, and technologies need to be found to recycle them back into the optimal processes. This optimization should be done in a holistic way so that the by-products and the ratio of inputs/outputs can change over time due to the implementation of new (low carbon) technologies, while the most optimal processes are found for each flow.

The different industrial processes also produce by-products/waste. For the range of by-products/waste for which no useful application exists (yet), technologies are needed that recycle them back into the optimal processes. Within their own value chain or being used by other process industries, maximising synergies between them.

With the ambition of **near-zero wastewater discharge**, the materials currently contained in the wastewater will at least partially be looped back into the processes as secondary resource again using innovative separation technologies closer to the generation point. New processes are needed again to upgrade these.

Finally, CO<sub>2</sub> (and CO) capture and utilisation provides carbon as a (secondary) resource for carbon-based materials or synthetic fuels (e.g. as final fuels or as renewable electricity storage).

New business models will be required to achieve industrial-urban symbiosis (I-US) and circular economy. This includes new business models and platforms for optimal supply chain for secondary resources as they will appear as heterogeneous and less concentrated flows.

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

- Insufficient appropriate methods (technological and economic) for sorting / separating (including sensing) mixed waste streams into recyclable streams;
- Complex composites consisting of combinations of materials (including multimaterials) which cannot be recycled as a combination or separated;

- Recycling/material recovery technologies are unavailable or 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.

### Primary resources

The strong increase of the availability of secondary resources (even with increased urban mining and landfill mining) will be insufficient to provide the process industry's full resource needs. Therefore, primary resources will still be needed.

Bio-based resources will increasingly be used as primary resources, requiring new, often aqueous, processes. This poses new challenges for industrial processes. There will be a need for regulation and certification systems to ensure the sustainability of the biomass.

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. These virgin materials will be procured with low-carbon certification.

### 3.2.2 Energy

Process industries are characterized by high energy consumption. This is notably due to the fact that raw materials (or wastes) do contain high amounts of contaminants, supporting materials, side materials etc. In order to disclose this, relative high amounts of energy will be needed to come to clean, purified primary or secondary materials.

In order to transition to climate neutrality, the process industries will focus on the use of the most sustainable energy forms. Electricity needs to be produced without GHG emissions in 2050. Consequently, the current emissions from electricity consumption (about 131 MtCO<sub>2</sub>) will decrease to net zero in 2050.

This also involves the shift to a different energy mix (e.g. direct renewable electricity with the addition of H<sub>2</sub>-based energy to attain high temperature needed in a furnace at a certain moment). However, this comes with the need to deal with increasing fluctuations in the supply of electricity using new solutions, including demand side management and integration of local energy storage at process industries sites.

The bottom part of Figure depicts the energy consumption of the process industries. The processes of the process industries (as well as the new processes needed to process the alternative secondary resources) will need to be adapted to avoid GHG emissions. Some new technologies, such as carbon capture and utilisation (CCU) routes<sup>10</sup> will increase energy demand, meaning that this additional energy should also be GHG emission-free.

**Energy efficiency** will significantly reduce the size of the required effort to reduce all energy related GHG emissions, while (most often) improving the competitiveness of processes. In many existing processes the thermodynamic limits of energy efficiency are nearly reached. A next generation of energy efficient technologies, especially in new processes, that drastically reduce energy consumption (like process intensification, enabled by 3D-printing of process equipment, and new separation technologies) is to be delivered. To some extent energy efficiency can be improved by applying more incremental technologies that improve performance by only a few percent. Especially in an increasingly complex system of energy and material flows, digital technologies can be applied to rapidly optimise efficiency.

The input of low energy content feedstock (e.g. Al-scrap) can also have a high impact on the energy demand. Efficient sensing and digital approaches (notably for sorting processes) will be needed to avoid higher energy costs due to “dirty” secondary materials.

<sup>10</sup> This roadmap only focuses on the CCU applications where the CO<sub>2</sub> or CO is used in a process, and excludes its physical use (as is done for example in CO<sub>2</sub>-enhanced oil recovery)

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 that directly use renewable energy (for example solar radiation) to produce materials are being developed and combined to achieve higher end-to-end energy efficiency. As nearly two third of the CO<sub>2</sub>-emissions (473 Mt CO<sub>2</sub>) are coming from the combustion of fossil resources a decarbonization of these processes will be done by moving to low carbon electricity among other sources). This means that the renewable electricity needs for the process industry will move up to more than 6500 TWh (whereas the full renewable energy production in the EC is nowadays only around 1000 TWh).

**Hydrogen**, for which different new GHG emission-free production routes will be developed, will increasingly be used to provide the energy input to drive reactions, or act as a reactant or feedstock. As such, it also enables many CCU processes. At the moment around 8.3 Mln tons of H<sub>2</sub> (HydrogenEurope <https://hydrogeneurope.eu/node/1691>) is used and responsible for about 59 MtCO<sub>2</sub>. A rough estimate by several sectors foresees an increase of H<sub>2</sub> use by 2050 of about 5 times. This creates a need of roughly 40 Mln tons clean H<sub>2</sub>. 45% of the needed H<sub>2</sub> is used by refinery, 34% for ammonia production, 5% for methanol production, 7% for other chemicals, 8% for other applications and only 1% for energy.

Remaining **thermal energy demand** can be provided by various alternative energy sources. For higher temperatures electricity can be used by developing electrical furnaces/kilns (which in some cases also generate process efficiency gains), and for lower temperatures heat pumps (again leading to efficiency gains) or flexible hybrid boilers (operating on renewable electricity when this is abundantly available) can be used. Bioenergy, waste, synthetic fuels, solar and/or geothermal energy can also be used to provide heat. The best energy source will be selected depending on regional circumstances<sup>11</sup>. Excess heat can be used in other applications, for example to generate power, in industrial symbiosis or to provide heating to urban areas.

### 3.2.3 CO<sub>2</sub> emissions

Most CO<sub>2</sub> currently generated is associated with energy supply and can be avoided using the options mentioned above. In some processes, however, CO<sub>2</sub> is formed as a by-product of the intended reaction (for example, CO<sub>2</sub> 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 (for dedicated long-term applications) and Carbon Capture and Storage (CCS).

## 3.3 Sector-specific status and innovation needs

Process4Planet is focusing on cross-sectorial approaches. But although challenges are cross-sectorial often solutions are sector specific. On top each sector also has several specific sector needs in order to realize fully the proposed ambitions. This section presents sector-specific challenges and considerations for each of the sectors participating in P4Planet. Often significant innovation is needed to harvest the potential mentioned in this section.

### 3.3.1 Minerals

The IMA members annually produce 180 million tonnes of industrial minerals for EU-28, Turkey, and Norway. Its products are calcium carbonate (precipitated and ground), dolomite, limestone, lime, bentonite, diatomite, talc, kaolin, plastic clay, sepiolite, andalusite, magnesite, silica sand

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<sup>11</sup> For example, in Southern Europe (e.g. Spain, Italy, Greece) there is opportunity for photovoltaic or concentrated solar power generation. The most effective solution will depend also on local urban energy demand.

and borates. Recycling rates vary between 35% and 63%,<sup>12</sup> with an average of 50% (IMA Europe, 2018). 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 which are recycled back into that same material (such as glass) at their end of life, thereby no longer involving the minerals sector as user of the recycled material. The sector itself **does not use many secondary inputs**. 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 restoration. The amount of waste from the production process is unknown.

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.

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

- Around 30% of the lime sector's 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 CCU and CCS), with electricity to heat kilns still requiring extensive R&D.
- The other 70% of the sector's own emissions are **process emissions** (CO<sub>2</sub> emitted during the process, resulting from the decarbonation of limestone; in other words, these emissions come from CO<sub>2</sub> chemically trapped in the stone), for which CCU and CCS appear the most logical/only solution with the current processes

### 3.3.2 Cement

Although concrete products have a long-life time, the redevelopment of buildings and infrastructure creates large amounts of demolition waste. 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.

Several waste streams can be fed as secondary resources into the cement production process. Its potential is influenced by the availability of secondary resources near the cement plant, which can vary significantly from site to site.

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 1,450 °C**; the kiln can be fired by fossil fuels (natural gas, coal) but this is being replaced more and more with alternative fuels (waste derived fuels, tyres, etc.). 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.

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<sup>12</sup> 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.

During this process, calcination occurs (decarbonation of limestone) where CO<sub>2</sub> is released (**process emissions**) and then clinker is formed; 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<sub>2</sub>-containing combustion gas to produce calcium carbonate.
- The cement industry actively researches the opportunities of re-carbonation (adding CO<sub>2</sub> 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.

### 3.3.3 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 upcycled material in new products is currently limited (to below 5%) to avoid undermining the quality of the product (CEPS, Economisti Associati & Ecorys, 2017).

Most end-of life ceramics are found in construction and demolition waste, mixed up with other materials. If the adequate technologies would be developed, all ceramics currently landfilled could be reused to make new ceramics, and there is a wide potential to use non-ceramic waste as secondary resource.

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 downcycled (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). In 2015, 70% of the required water in the Italian ceramics industry was **recycled wastewater** (Ceramica, 2019).

Fuel is combusted to obtain the **high temperature needed** for the processes (including sintering, but also drying processes). There is 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).

According to the sector's 2012 roadmap electrification could be possible (particularly for large kilns), but this is not yet economically viable or demonstrated (Cerame-Unie, 2012). Besides electricity, bioenergy or hydrogen can be used to replace fossil fuels if new burners are developed and tested to ensure quality of the produced materials. The **process emissions** can be mitigated using CCS or CCU, but there are challenges due to the relatively small size of the installations.

### 3.3.4 Refining

The refining sector produces a wide number of different products used either as feedstocks for other process industries (e.g. petrochemical) or as final products to satisfy the final demand for

liquid fuels and products in transport and in other industrial applications. The refining process industry, historically based on petroleum as its main feedstock, has started its transformation aiming to contribute to meeting the 2050 climate neutrality challenge. In order to achieve so, a combination of key technologies have been identified which are being developed, scaled-up and deployed in many plants across Europe to reduce the GHG intensity of the final fuels and related refining products in the 2020-2050 timeframe (some of them being already at industrial scale).

Some of the key GHG mitigation technologies identified for the transition, at different TRL levels and with clear synergies with the other process industries part of Process4Planet, can be clustered in big families:

- Improvements in refinery **process energy efficiency** reflecting changes to the technical configuration of individual refineries or increased recovery of low-grade heat with innovative and more efficient technologies.
- Use of **low carbon energy sources**, increasing use of low-carbon electricity, substitution of fired heaters ( $T > 500^{\circ}\text{C}$ ) by electric ones, production of hydrogen (as feedstock) on a low carbon intensive manner (e.g. water electrolysis, steam methane reforming coupled with carbon capture and storage) or integration of renewable feedstocks for heat production.
- **CO<sub>2</sub> capture** at the refinery site will be essential driver towards climate neutrality. Capture technology improvements in terms of both capture rate, energy efficiency and cost reduction are common elements in all CO<sub>2</sub> re-utilisation schemes (enabling carbon capture and storage as well).

Beyond the above-mentioned technologies, with a significant potential for both direct (and indirect) emission reduction, the challenges for the refining sector go beyond its boundary limits and expand them from the production site towards how to mitigate GHG emissions associated with the final use of one of their main products (fuels). The main reason behind is that, when the whole Well-To-Wheels fuel value chain is considered (from the production to their final use in the engines), the combustion of fuels in transport is responsible for ~80% of the total GHG emissions with around <10% linked to the refining process. In this context, the gradual replacement of petroleum by **renewable and waste feedstocks** into the refining processes, as well as the development of their related conversion technologies (e.g. biomass-to-liquids, pyrolysis, CO<sub>2</sub> to synthetic fuels), is considered as one of the most important contributions from the sector towards an EU climate neutral economy. Not only will this enable higher levels of circularity and waste valorisation but it will have the potential to impact significantly on the GHG emission reduction across the whole value chain and could increase the speed of the transition as these new Low Carbon Liquid fuels can use the existing distribution infrastructure and do not require a renewal of the entire vehicle fleet.

### 3.3.5 Chemicals

Chemical products, building blocks and materials are indispensable to almost all value chains and industries, from automotive, aeronautics, electronics, energy, construction, textiles, pulp and paper, to healthcare, agriculture and food. Sustainable chemistry being such a key enabler for the entire economy, has a major role to play to drive the changes and develop solutions to address pressing global challenges, such as climate change, the need for a more circular economy, the smarter use of resources, and environmental and health protection.

Sustainable advanced materials made by the chemical industry contributes to European industrial competitiveness, environmental performance and the circular economy, by improving energy and resource efficiency as well as via circularity-by-design. In the context of transitioning to a circular economy, some key challenges include the sustainable recycling of materials, which goes beyond materials innovation and includes synergy with advanced processes and the opportunities that digital technologies can offer.

To reach ambitious targets regarding climate change mitigation and circular economy, disruptive process technologies must be developed in addition to leverage further process efficiency options for existing technologies:

1. Novel process technologies will allow to largely increase the share of climate neutral energy through indirect (power-to heat) and direct electrification of chemical processes, including through alternative energy forms (e.g. plasma, microwave etc.), hydrogen and possible direct utilisation of sunlight as longer-term conversion technology option;
2. Utilization of alternative carbon sources such as biomass, including waste streams, CO<sub>2</sub> (and CO captured from industrial effluents) and waste materials, e.g. plastics waste;

Carbon, as a chemical element, is a crucial building block of countless essential chemical components and the basis of the entire organic chemistry. In order to decouple chemicals production from the exploitation of fossil resources, a key challenge of our times is to design and scale up technologies enabling the chemical sector to move towards so-called “sustainable carbon sources”. These carbon sources include CO<sub>2</sub> (and CO) captured from industrial effluents, (fossil) waste streams (e.g. plastic waste), biomass (waste). This transition will require extensive amounts of climate-neutral energy carriers (e.g. electricity, hydrogen).

3. Advanced separation and recycling process technologies will enable critical raw materials and efficient wastewater recovery and reuse;
4. Digital technologies applied ranging from product-design to process- and plant-control including the management of connected process and industrial symbiosis will greatly influence resource and energy efficiencies. Tracking of products along value chains through digital product passports including distributed ledger technologies will be key enablers for circularity and materials recycling. The chemical industry must leverage and implement digital technologies (e.g. blockchain, big-data and artificial intelligence, digital twins).

### 3.3.6 Non-ferrous metals

Non-ferrous metals, like aluminium, copper, nickel, silicon and cadmium, are used in a diverse range of applications and sectors. They are mostly used in transport (29%), followed by construction (24%) and industry (19%). Packaging (11%), batteries (11%), and durables (5%) complete the list (Eurometaux, 2015). Non-ferrous metals supply into the EC’s “strategic value chains” (like batteries, renewables and ICT).

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:

- Innovations to allow for efficient and climate friendly recovery (inclusion 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, including:

- Scrap (pre-)processing for improving scrap quality (cooperation ferrous and non-ferrous sectors);
- Separation of scrap through the application of advanced physical separation techniques (e.g. sorting, shredding, size, and density classification) should be further developed;
- Removing metallic coatings of tin and zinc (currently limited economically viable solutions based on hydrometallurgy or thermal treatment are available);
- Possible treatment of residues from ferrous and non-ferrous 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 and chromium by exploring pyro- or hydrometallurgical as well as mechanical/physical treatment routes;
- Technologies to recover ferrous and non-ferrous metals from residues from their production and from waste incineration residues (currently partially landfilled);
- Large exports of scrap and products containing metals can be stopped, particularly to regions with poor recycling regimes, increasing thereby the resilience of European society and reducing its dependency on imports of primary resources;
- The required infrastructure should be set up for new products such as electric vehicles, solar panels and wind turbines;
- Improve the end-of-life recycling of vehicles;
- Increase the recovery rates of waste electrical and electronic equipment: 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;
- Establish new value recycle value chains for value chains in which non-ferrous metals have only recently been introduced (for example, the amount of aluminium in cars has been increasing).

**For 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 is still room for improvement in the packaging market (60-70% recycling rate), for instance in multi-layer packaging with thin films of aluminium. In all cases, moving to higher quality recycling is beneficial, especially in the future since aluminium supply will be more based on recycling.

**For copper:** From a life cycle perspective, the carbon footprint of recycled copper is lower than that of primary copper. The carbon footprint can be further reduced by improving the quality of the scrap, for example with innovative processes that remove adventitious carbon from secondary copper originating from electronics waste. Improving the quality of the copper scrap will reduce the energy required for its upcycling.

Beyond aluminium and copper, the recycling of several other non-ferrous metals delivers positive impacts for climate, circularity and resilience of our European society.

Non-ferrous metal production is electricity intensive: 58% of the energy input is in the form of electricity (69 TWh) (Eurostat, 2020b). Natural gas accounts for another 35% and the balance is for oil products, solid fossil fuels, and others (Wyns & Khandekar, 2019).

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 (Wyns & Khandekar, 2019). However, the largest share will come from decreasing the GHG emissions of the power sector, which is outside the scope of P4Planet. **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 perfluorocarbon (PFC) emissions from aluminium production have been nearly eliminated.

### 3.3.7 (IMA Europe, 2018) Steel

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. Energy and carbon (coking coal) are used to separate iron from oxygen in an (energy-intensive) blast furnace; besides coal, electricity and natural gas are used;
- 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;
- Scrap processing is further mentioned under non-ferrous metals (3.3.6)

In both routes, the liquid steel produced is casted and then shaped or rolled into its final form. A third route to produce steel, direct reduction of iron using natural gas, is only applied at one site in Europe.

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

The quality of the scrap determines to a large extent the quality of the material. Secondary steel cannot be used to serve all end-markets. Next to the quality, the availability of scrap is the limiting factor to increase the share of electric steel making. Stock turnover of steel-containing products typically takes 5-50 years, or even longer. Models show that the primary steel production will need to be necessary even beyond 2050 (ArcelorMittal, 2019).

To accelerate the GHG emission reduction and align with the ambitions, the steel industry can 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-sectorial coupling, for example by combining fossil-based process integration, including new steel production processes, with **carbon capture and storage and utilisation**.

Under Horizon 2020 the steel industry worked together with other energy intensive industries in cross sectorial topics and continue to do so. P4Planet and the proposed partnership Clean Steel will align their R&D objectives and plans on a regular basis.

### 3.3.8 Water

The biggest part of the large European wastewater plants was built thirty to forty years ago. Their only purpose was to remove the organic pollution from the wastewater. Thus, while water is naturally circular, it is not yet the case of the water sector itself. Currently, more than 40,000 million m<sup>3</sup>/year of wastewater is treated in the EU, of which only 964 million m<sup>3</sup>/year is reused (EC, 2017). Industry is one of the main water users in Europe, accounting for about 40% of total water abstractions (Eurostat, 2014).

There is potential to increasingly valorise the many different components in (industrial and municipal) wastewater, applying a large variety of technologies.

The use of sludge from wastewater treatment varies strongly over the various member states, with around 20-40% incinerated and around 10% landfilled (refer to innovation programme Wastewater valorisation).

The GHG impact of the European water sector is driven by its electricity **consumption** and by the **process emissions from the wastewater 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 GHG emission-free 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 and nitrous oxide (not in scope) and CO<sub>2</sub>. There thus is a clear space to increase the circularity of industrial wastewater, in symbiosis with urban wastewater, aiming for (near) zero water discharge (thus recycling a much higher share of the water, including from the municipal sector to industry) and valorising more components in the wastewater. Furthermore, wastewater is sometimes discharged at elevated temperature, with the potential for heat recovery and the production of energy carriers through anaerobic digestion of hydrocarbons (water-energy nexus).

### 3.3.9 Pulp and Paper

The pulp and paper industries, also referred to as the forest-fibre and paper industries, had a total turnover of € 81 billion in 2016 and employed about 175 000 people. As well as using virgin forest fibres, the European pulp and paper industries are one of the major recyclers in Europe. They reached a world record paper recycling rate of 72.3 per cent in 2017 (which is close to the theoretical maximum), while 90 per cent of newspapers and corrugated boxes are made from recycled fibres.

The Pulp & Paper sector is a part of the forest-based value-chain, which in Europe provides society with a wide variety of products and services, ranging from paper, packaging, tissue paper and furniture, to carpentry and construction materials, wood-based panels, textile fibres, biofuels, bio-energy, chemicals and still much more. . The forest-based value-chain provides around 8 per cent of the EU's total manufacturing added value and creates close to 4 million jobs. Forest available for wood supply cover one-third of the EU's landmass and provide income for approximately 16 million forest owners, and thousands of employers in public forest management organizations.

About 60% of the fuel used in the pulp and paper industry is biomass, coming from sustainably managed forests. Biomass is both a raw material and an energy source for the sector. This characteristic places the sector already well ahead on the path to decarbonisation and provides opportunities for developing new carbon-neutral products and solutions beyond the traditional pulp, paper and board products.

However biomass is not equally spread across the sector. Where access to biomass is not possible, fossil fuels make up for the remaining share of fuels used, with natural gas taking the lion share and being responsible for about 75% of the residual carbon emissions. The sector is exploring all possible options to reduce carbon emissions from combustion of fossil fuels. These include: **electrification**, **on-site integration of renewable energy sources** (geothermal, solar thermal, biogas...), and **process efficiency** (digitalisation, optimisation of unit operations as well as breakthrough technologies). Each of the options under development has its own challenge, in terms of R&D, risk management, limits in volumes of energy produced, CAPEX and (in case of electrification) OPEX costs.

The pulping processes currently applied are very effective and CO<sub>2</sub> neutral. They isolate high quality cellulose fibres, while the remaining lignin serves as a sustainable energy source feeding the process and pulping chemicals are being recovered. However, the increasing demand for biobased feedstock to replace fossil feedstock for chemicals and materials, calls for pulping

processes with lower energy demand allowing the lignin side stream to become available for new materials while keeping a CO<sub>2</sub> neutral process.

The paper making process generally consist of disperging recycled and/or virgin cellulose fibres in water, formation of the paper web and removing the water by pressing and thermal drying. On average 70% of the energy required for paper making is used for thermal drying.

Larger steps in process efficiency can only be realized when breakthroughs are realized in the main energy consuming steps in pulping and papermaking. For pulping this means **milder fractionation technologies**. For papermaking this means either reducing the amount of water to be evaporated (**breakthroughs in mechanical dewatering or papermaking without water**) or requiring less heat for this water removal part (**innovative drying and heat recovery technologies**).

When looking at the challenges in coping with extreme events due to climate change, one of the most relevant aspects is access to water.

The industry needs about 3.5 bn m<sup>3</sup> of water per year, primarily from surface water. Even though around 90% of water abstracted to produce paper and board is returned to its source after treatment, access to water at a time of droughts or floods is progressively becoming a challenge in keeping a smooth functioning of the operations. This requires increased stability in closed-loop systems and process water recirculation, as well as **energy-efficient and high-yielding separation and extraction technologies**.

The sector is also predominantly present in rural areas: this gives the opportunity to develop local partnerships to valorise biogas production and consumption. It can also stimulate a more circular economy, integrating biologic waste streams across industries, thus strengthening local value-chains.

### 3.3.10 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 both within Europe and largely outside of Europe. An increasing share of innovation/patents are coming nowadays from the RTOs and the engineering sector before being supplied to industrial production. Therefore, they are innovation partners to the process industries. 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 optimisation of the positioning of equipments within the available space is still largely manually achieved, leaving a large remaining potential for further reduction of the use of building materials (notably concrete). 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.

### 3.4 Hubs for circularity

The cross-sectorial and regional dimension of the outlined innovation challenges must be considered. Process industries are often clustered in industrial parks to benefit of advantaged energy, services, infrastructure and material flows. There is still a significant opportunity to further develop this approach, enabling circularisation of value chains through advantaged flow materials, side streams products and secondary materials across industrial sectors and with the urban environment, triggering the development of regional hubs for circularity. Business cases identified in regions will connect local stakeholders and drive innovation based on potential integration synergies for process industries (see Text box 2: Regional infrastructure needs on regional infrastructure needs). That is why the implementation of Industrial-Urban Symbiosis and Circularity needs to take place predominantly in regions<sup>13</sup>. Some EU regions have ambitious objectives like those of P4Planet, for example “Climate neutral region” or “zero-waste region”, and this can boost the regional development of Industrial-Urban Symbiosis and Circularity. Nevertheless, when it comes to the provision of secondary resources, interregional value chains may need to be established as well where critical mass of materials for relevant processes needs to be reached for process feasibility and optimized LCA.

Industrial Symbiosis means long-term commitments across the boundaries of individual organisations when dealing with wastes and by-products. This 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 other reasons due to “fragmented” ownership, misaligned corporate interests, lack of knowledge about the potential of symbiosis and circularity in regions and the lack of experience in funding collaborative ventures.

Building trust, elaborating on potential business cases for the region and bringing the relevant stakeholders around the table to discuss the creation and distribution of advantages from symbiotic relations can be facilitated by a neutral and knowledgeable third party. Such facilitators might not only support the regions in overcoming the barriers, but also be a knowledge-managing link on an EU level between regions so the regions will optimally profit from best available practice and share new one.

The P4P concept of Hubs for Circularity (H4C) is based on discussions with regions where initial facilitation structures are already in place or under development. Some of them have already shown initial results.

#### **Text box 2: Regional infrastructure needs**

As crucial as it can be, a geographical proximity approach cannot alone deliver a climate-neutral and circular economy. The achievement of these transformative objectives will also require a more regional approach, through changes to the infrastructure that is used to transport energy and materials. Existing electricity infrastructure needs to be upgraded to enable handling the increasing demand. Existing gas infrastructure can be reused for transportation of biogas or hydrogen. The gas transmission networks and interconnecting pipelines in Europe could include blending of hydrogen in the natural gas without modification. Converting parts of regional gas

<sup>13</sup> Note that regions here can be smaller (e.g. city) or larger geographical area, potentially even across borders

pipeline infrastructures in Europe to transport 100% hydrogen would enable more conversion of green electricity to hydrogen which could then be distributed to industry and process users. This approach could be further developed for a dedicated pan-European hydrogen pipeline. This would enable production and interconnection of GHG emission-free hydrogen and electricity at scale necessary to transform the European process industries. Since gas infrastructure is typically less expensive than high voltage transmission lines, this route can be favourable, certainly in the shorter term.

Not all industrial sites in Europe will have access to the same types and quantities of GHG emission-free 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 will depend on developments in energy transport, via high voltage transmission lines, gas, and other solutions.

Beside energy infrastructure, waste collection and transportation infrastructure are also essential for the transition and dependent on the regional situation.

To be able to rapidly develop infrastructures regionally, interaction between multiple stakeholders (industry, waste sector, local authorities, city planners, etc.) is necessary. Plans of multiple stakeholders should be following the same goals. The bottom-up and top-down activities need to be regularly cross-checked and followed up on different levels (local, regional, national, and EU level).

### 3.4.1 Defining Hubs for Circularity

H4Cs are self-sustaining economic industrial ecosystems for full-scale Industrial-Urban Symbiosis and Circular Economy, closing energy, resource and data loops and bringing together all relevant stakeholders, technologies, infrastructures, tools and instruments necessary for their incubation, implementation, evolution and management.

**They are facilitated regional initiatives** that involve regional stakeholders and aim to realize ambitions related to **circularity and/or climate neutrality** around their industries, but they also look across regions, whenever the necessary loops for building circular value chains need it according to the availability of resources, LCA and for knowledge exchange. The initiatives also address **regional demands** (public and private), such as infrastructure needs or health and safety.

H4Cs will connect potential **industrial-urban symbiosis stakeholders**. H4Cs involve companies (large companies and SMEs) and connect to civil society, local authorities, RTOs, etc. All actors are committed to realizing the ambitions of the region, sharing competences and resources as well as jointly identifying regional needs and opportunities. A circularity culture will be developed to reduce GHG emissions and waste and co-develop solutions. Industries will become more open and trustful and will be committed to collaborate closely through new business models supported by local authorities to de-bottleneck permit processes and provide co-investment funds.

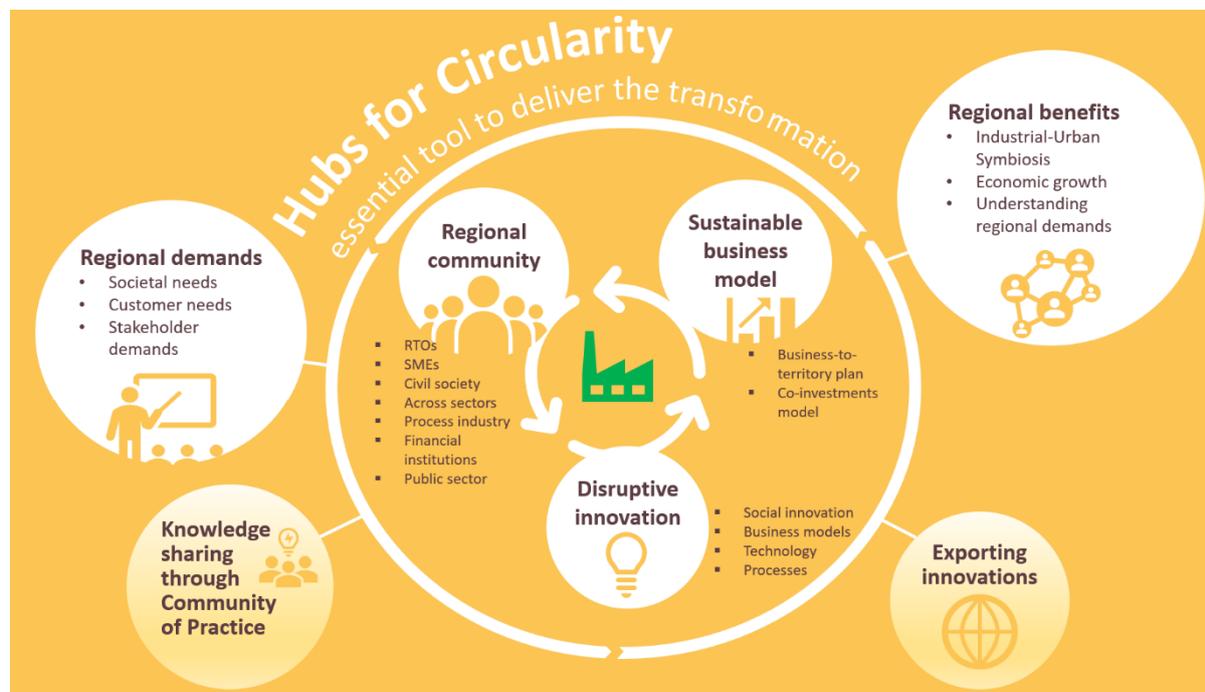
Studies have shown that a neutral facilitator is key to create necessary trust, keep momentum and effectively develop the hub-culture<sup>14</sup>. We recommend the regions to create their facilitation services and connect to a dedicated SPIRE Community of Practice for knowledge and best practice exchange.

The H4Cs will identify and develop business cases, tailor made for their region (**business-to-territory** approach) that will enable businesses to effectively turn collective problems and needs into advantageous and viable business opportunities. This will add value to businesses and

<sup>14</sup> Most notably, the unpublished independent expert report “Study and Portfolio Review of Cluster of Projects on Industrial Symbiosis in Directorate Prosperity in DG R&I: Findings and Recommendations – Policy Report”

stakeholders, triggering large-scale deployment and **co-investments**, which can involve European, national, regional and industrial funds.

H4Cs are expected to have a **sustainable operating model** that facilitates continuous improvement of the region's performance and can respond to shifting needs. Knowledge sharing will take place in a coordinated fashion, both within the H4C and between EU regions, so H4Cs (and others) can learn from each other. 10 summarizes the key components and workings of H4C.



**Figure 10: Key components and working of a Hub for Circularity**

Due to the multi-stakeholder approach, the H4Cs are expected to create the right conditions for the innovation and its implementation. As specific material flows will frequently need to be scalable, collaboration beyond the limits of individual hubs will be required. Social innovation will need to be part of the whole to create customer awareness and acceptance, and to promote education and development of new skills.

### 3.4.2 Development of Hubs for Circularity

Several examples of facilitated industrial symbiosis in regions and industrial parks exist today that can give inspiration for emerging H4Cs: Kalundborg (Denmark); Smart Delta Resources (Netherlands); trilateral region of North Rhine Westphalia (Germany), Flanders and the Netherlands, Mo Industrial Park (Norway) or Eyde Cluster (Norway) and many more. An increasing number of projects is put in place to incubate structures leading to building hubs, such as projects responding to SPIRE-1-2020 or project INCUBIS (an energy symbiosis incubator for supporting waste heat and cold valorization in industrial parks, zones and districts.) – to name very few.

Different regions face different challenges to meet sustainability ambitions and find themselves at different levels of development with respect to a hub-culture (mainly due to different industrial histories, structures and geographical characteristics). Figure 5 shows an attempt of classification of the hubs. There is a pathway to be followed to achieve a high levels of integration within a given Hub. Beyond technological aspects, many other hurdles have to be overcome (regulations, skills, culture, ...), In other terms, the achieved level of circularity can be related both to the achieved

Technological Readiness Level (TRL) and to the so-called Symbiosis Readiness Level (SRL), which encompasses all required non-technological innovations.

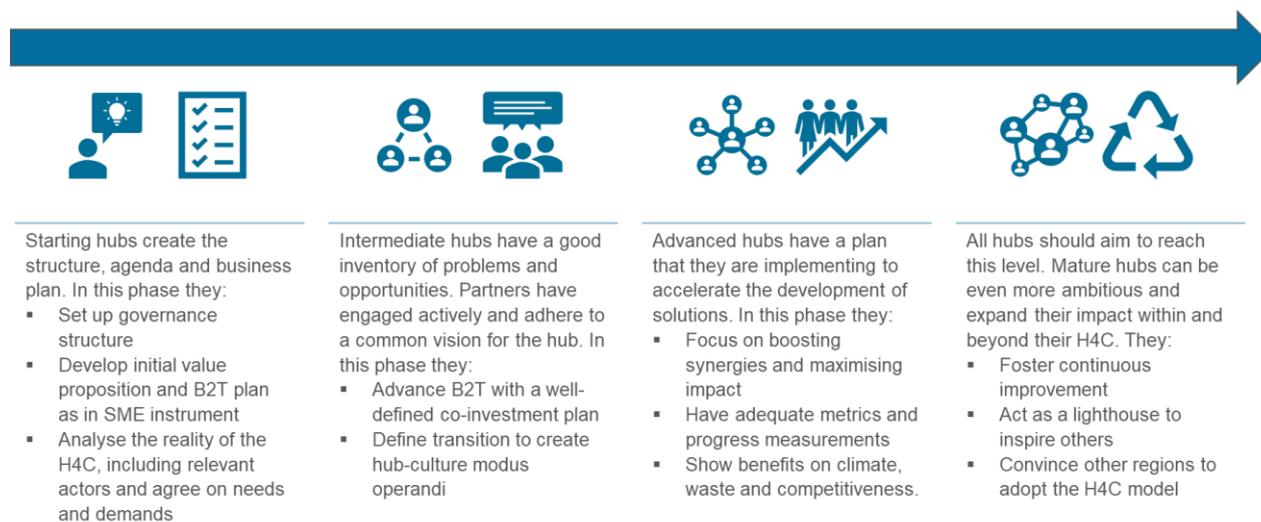


Figure 5: Different maturity levels of Hubs for Circularity

Section 4.13 describes how P4Planet aims to support the creation and development of H4Cs.

### 3.4.3 Benefits from Hubs for Circularity

The H4C provides numerous regional benefits:

- **Industrial-Urban Symbiosis:** the concept of industrial-urban symbiosis (I-US) is not new, and non-technological barriers to the implementation are known to exist. Hubs of circularity are expected to help to overcome these barriers and to accelerate the transition towards a circular economy.
- **Optimization of production systems:** through I-US, production systems become more resource efficient, which saves costs and contributes to environmental objectives.
- **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, I-US results in efficiencies for process industries, water utilities and other companies, saving costs. Third, the interaction boosts innovation and exporting the developed innovations brings additional revenue to the region. Finally, the hub attracts 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. The improved quality of the educational system attracts further talent.
- **Understanding regional potentials:** as the H4C mature, the understanding of regional demands and potential synergies increases.
- **Social acceptance:** the involvement of all stakeholders in the region ensures that local stakeholders are better informed and supportive of the innovations delivered by the H4C.

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

## 3.5 P4Planet in the EU innovation landscape

<< This section is still being drafted by A.SPIRE. It will be shared for review in a separate document >>

## 4 P4Planet's innovation portfolio

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This chapter provides an overview of the portfolio of disruptive innovations that P4Planet aims to achieve. At first, in Section 4.1, the overall overview of the innovation areas is presented, after which Sections 4.2 to 4.15 describe each of the innovation areas. These sections contain hyperlinks to Appendix A to easily find more details about each of the innovation areas.

### 4.1 Innovation overview

Analogous to Figure 9, Figure 12 and 13 provide an overview of the innovation programmes summarised in this chapter, presenting how they deliver the desired future state. Note that for clarity the figures are shown separately, but in practice there are interlinkages and trade-offs between the resources and energy dimensions of the process industry, for example when energy consumption is determined by the resources that are being used in the process.

The remaining sections of this chapter detail what innovation is programmed for these innovation areas in the P4Planet Roadmap – following the same flow as in Section 3.2:

#### Resources

- The innovations aiming at producing **innovative better recyclable materials** are described in Section 4.11;
- The innovations aiming at **increasing the use of secondary materials** are presented in Section 4.10 and for Carbon Capture and Utilization in Sections 4.7-4.9;
- **Valorisation of valuable substances in wastewater** and preventing its discharge is presented in Section 4.10;

#### Energy

- The innovations increasing **energy efficiency** are presented in Section 4.10; the innovations in Sections 4.3-4.5 also lead to an increase of energy efficiency;
- The innovations that **integrate increasing amounts of renewable electricity** are described in Sections 4.2, 4.4 and 4.5;
- The innovations associated with the alternative generation of **hydrogen**, its integration in the process industry and its storage are described in Section 4.6;
- The innovations aiming at **new technologies to deliver heat** are described in Sections 4.2, 4.3, and 4.4;

#### Accelerators

- The innovations strengthening **Industrial-Urban Symbiosis** and **Hubs for Circularity** are described in Sections 4.12 and 4.13;
- The innovations enabling many of the above through **digitalisation** are described in Section 4.14.
- How non-technological aspects that are key for successful innovation are addressed is described in Section 4.15

Note that the impact estimations that are presented in the innovation areas cannot simply be added up because many innovations overlap.

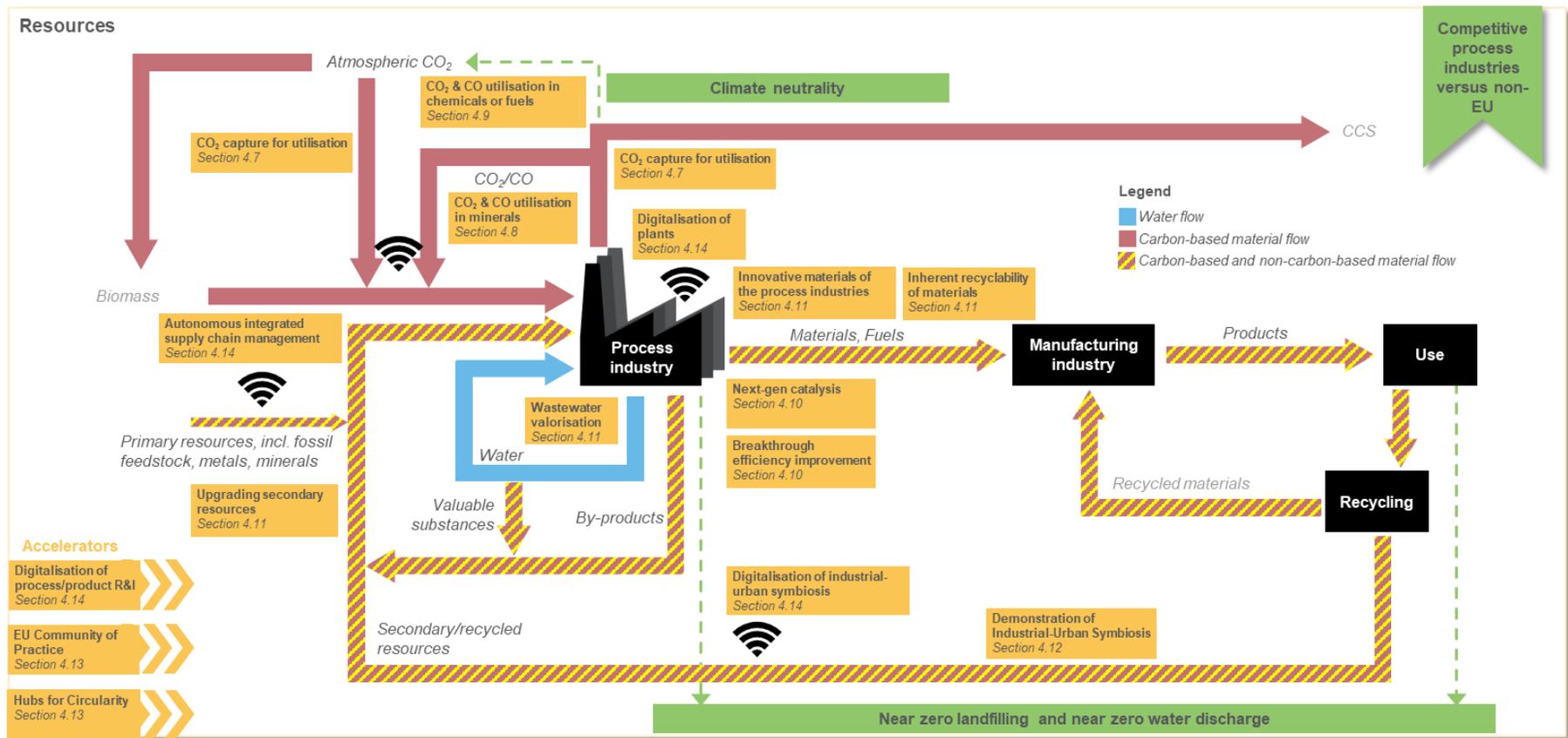


Figure 12: Required innovation mapped to the 2050 material flows related to the process industry

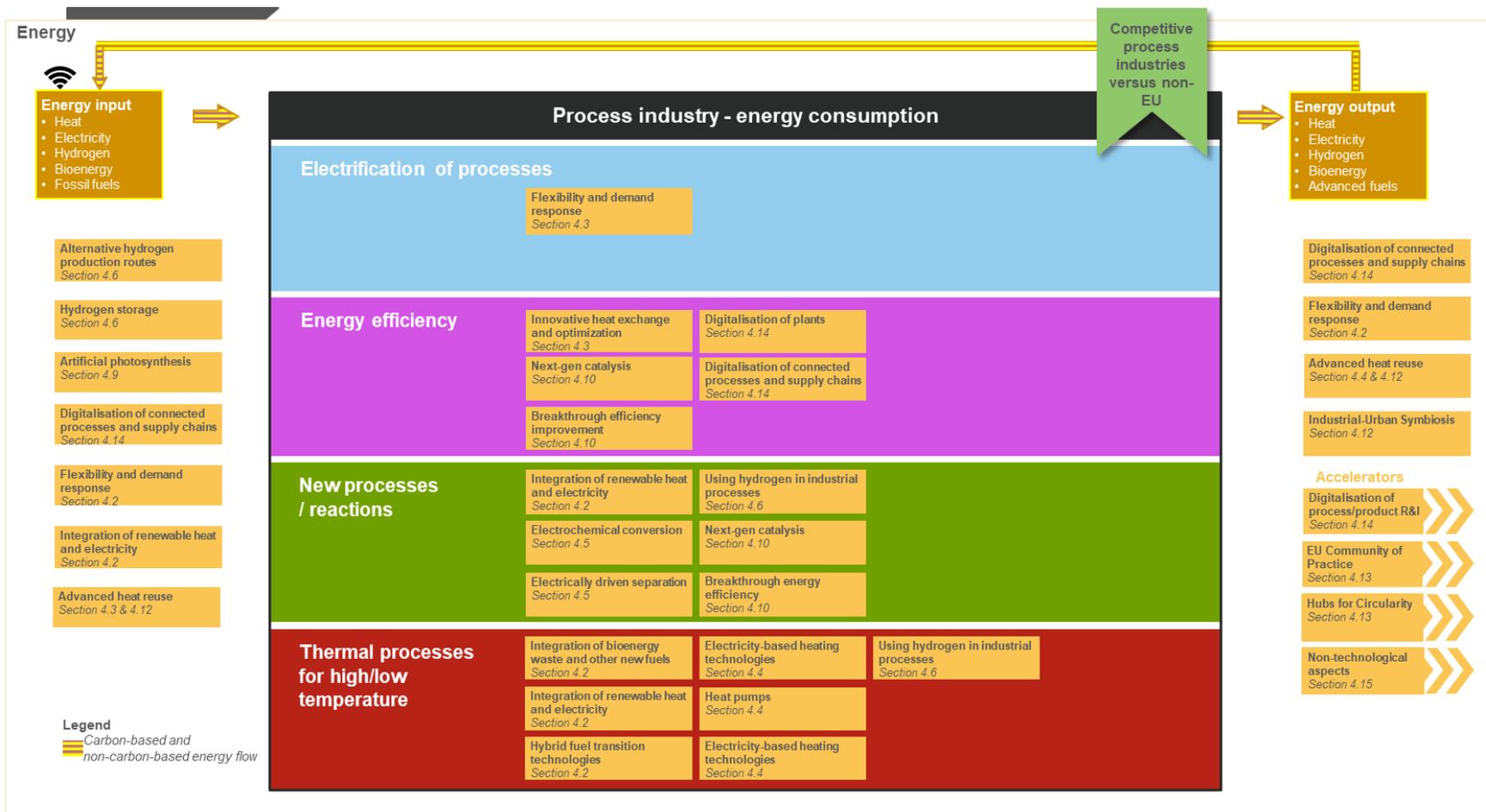


Figure 13: Required innovation mapped to the 2050 energy demands of the process industry

## 4.2 Renewable energy integration

European process industries will move from the current energy mix, which is dominated by fossil fuels and feedstocks, to a mix of various GHG emission-free 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 will be defined by the technological adaptations/developments in the envisaged processes.. However, directly integrating renewable energy generation with its use in the process industry can deliver higher overall efficiencies.

**Integration of renewable heat and electricity (A-1.a)** 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, reducing fossil fuel emissions by an estimated 10 MtCO<sub>2</sub> (e.g. PV powering a ceramics kiln, solar heat used for drying, or wind power for chlorine production).

**Integration of bioenergy, waste and other new fuels (A-1.b)** 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 transition technologies (A-1.c)** are key for a competitive transition. As several low-carbon fuels are expected to decrease in cost (e.g. hydrogen, ammonia or synthetic methane) 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 (for example, being able to directly use large volumes of GHG emission-free hydrogen when they become available). Hybrid modular systems are available and will be demonstrated at industrial scale. Integrated hybrid technologies will also be demonstrated.

Since the process industries are large energy consumers, they can accelerate the transition to renewable energy by entering into long-term purchase agreements with emerging renewable energy infrastructure projects. The key for this acceleration is an efficient energy storage system or process flexibility to account for the variable supply. 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.

Process industries need to innovate to deliver **flexibility and demand response (A-1.d)**.

Flexibility will be explored in existing processes, but process redesign to facilitate flexibility is also 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.

For these innovations to be deployed at scale it is key that enough renewable energy is available at competitive costs and that energy infrastructure enables these developments. The innovation programmes in this innovation area collectively can contribute to several hundreds of MtCO<sub>2</sub>e GHG emission reductions and when paired with other innovation programmes (e.g. electrification) can eliminate all fossil fuel-related emissions. 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.

### 4.3 Heat reuse

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 and there is potential for **advanced heat reuse (A-2.a)** technologies. Developing better heat exchangers increases the amount of heat that can be recovered by enabling heat recovery in heat flows where it currently is not yet possible to do so, and by improving the economics of heat recovery.

### 4.4 Electrification of thermal processes

Around 52% of the European process industries' own<sup>15</sup> 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 (A-3.a)** (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 above in 2035, increasing the range of processes in which heat pumps can be used significantly, enabling savings of 15 MtCO<sub>2</sub>. Moreover, effective use of heat pump technologies inherently requires exhaust vapor without contaminants and with low air content. Currently many industrial drying technologies result in a vapor with contaminants or too high air content so that latent heat cannot efficiently be recovered with heat pump technologies. The challenge is to innovate in the drying technologies in order to solve these issues (e.g. superheated steam drying, air/vapor separation, removal of solid contaminants) so that heat pumps can more efficiently be used. Because heat pumps deliver a multiple of the amount of electricity consumed in the form of heat, their application also increases the energy efficiency of processes significantly—and the available renewable electricity is used well.

When GHG emission-free electricity is used in **electricity-based heating technologies (A-3.b)** to replace natural gas, coal, waste or biomass, the fuel-related emissions are eliminated also for high temperature applications like reactors, furnaces or kilns. This deeply reduces the emissions of steam cracking furnaces (the start of the hydrocarbon value chain of the chemical industries) and eliminates (almost) all heat related emissions of both the ceramics industry and highly flexible electrically heated reactors with further potential in refineries. Electric kilns reduce the emissions of the cement and lime sector by around one-third (the heat related part of the emissions). In some applications, just the heating will be done differently, while in other applications switching to electrically heated furnaces or kilns offers the potential to also deliver efficiency gains in the process (for example for ceramics drying/sintering). The aim is to have electric heating technology fully developed for application in 2030 (ceramics and steam crackers) until 2035/2036. The price of renewable electricity needs to be sufficiently low to make these investments attractive. The total emission reduction enabled by this programme is 106 MtCO<sub>2</sub>.

### 4.5 Electrically driven processes

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 (A-4.a)** becomes attractive. This can be done in the steel, non-ferrous metals, cement, lime and chemical industries, to make fuels and potentially to produce cement by electricity.

Such electrochemical reactions can have applications for the production of various chemicals (including from CO<sub>2</sub>), hydrogen, steel, lime (also for cement), and chemicals like ammonia, ethylene (from methane), HMF, FDCA, non-ferrous metals, hydrogen peroxide and ozone. . Often, electrochemical reactions have no GHG emissions at all (when no emission electricity is used), and they do not produce waste that would need landfilling. There are many similarities

<sup>15</sup> Scope 1 corrected for auto-generation of electricity.

between the innovation needs for the electrochemical processes in the various sectors, and technologies are expected to mature gradually, until they can be applied in 2050 in processes emitting 261 MtCO<sub>2</sub>.

Separation of different components requires high amounts of energy. A wide range of **electrically driven separation technologies (A-4.b)** (e.g. pressure driven) are being developed for a wide range of applications. For water-based separations, these technologies enable cleaning wastewater 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 with much lower electricity consumption while simultaneously 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. These technologies have the potential to reduce CO<sub>2</sub> emissions by 15 MtCO<sub>2</sub> in 2050.

## 4.6 Hydrogen integration

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. 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. **Using hydrogen in industrial processes (A-5.b)** often requires serious changes to the furnaces/kilns, as hydrogen burns differently than the currently used fossil fuels and often requires new processes. These technologies have the potential to reduce emissions by 285 MtCO<sub>2</sub>, with additional potential when CO<sub>2</sub> is used as feedstock (CCU; see further on).

One of the key future production routes for hydrogen is the electrolysis of water, by which 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 and in oxidation reactions. Using oxygen symbiotically in combustion processes enables more efficient capture of the resulting CO<sub>2</sub>. Oxygen can also be used for water treatment application and fish farming at scale.

Replacing fossil fuels with 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 P4Planet, various **alternative hydrogen production routes (A-5.a)** 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<sub>2</sub>S* 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 an 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 biobased H<sub>4</sub>C/biorefinery, after all valuable components have been harvested

When developing these technologies, the overall sustainability of the processes needs to be assessed from a system perspective, including considering by-products / waste.

Other alternative hydrogen production routes could be developed as well, including using waste heat to boost H<sub>2</sub> production efficiency.

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. The emissions generated for the current production of hydrogen in Europe are between 70 and 100 MtCO<sub>2</sub><sup>16</sup>, which can (nearly) all be eliminated with these alternative hydrogen production routes.

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 for **hydrogen storage (A-5.c)**. Various 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.

#### 4.7 CO<sub>2</sub> capture for utilisation

Capture and purification of CO<sub>2</sub> 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<sub>2</sub> 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 and that tolerate more diluted streams to a certain extent, lowering the need for separation and thus gaining efficiency. This 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 materials.

**Flexible CO<sub>2</sub> capture and purification technologies (A-6.a)** should on the one hand focus on more efficient and modular post-combustion capture technologies (where the starting CO<sub>2</sub> concentration is relatively low), and on the other hand on purification technologies for CO<sub>2</sub> 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<sub>2</sub> emission reductions (around 250 MtCO<sub>2</sub>). Currently several kilograms of waste are generated with each tonne CO<sub>2</sub> captured, and the programme aims to reduce this waste drastically. Key success factors for this innovation programme are effective policies, a demand for CO<sub>2</sub> in CCU applications, and technologies that increase the CO<sub>2</sub> 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<sub>2</sub> concentrations) will be needed in the future as an alternative to capturing CO<sub>2</sub> from flue gas. The development of direct air capture can build on the other capture technologies.

#### 4.8 CO<sub>2</sub> and CO utilisation in minerals

Several types of minerals naturally bind to CO<sub>2</sub> (for example, olivine or caustic lime). This property of the material can be used to bind captured CO<sub>2</sub> and avoid this CO<sub>2</sub> 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<sub>2</sub> utilisation in concrete production (A-7.a):** Technologies exist for special concrete types (wollastonite) to bind CO<sub>2</sub> 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 12 MtCO<sub>2</sub>.

**CO<sub>2</sub> and CO mineralisation to produce building materials (A-7.b)** will be developed for recycled concrete, slag waste, and natural materials. After its lifetime, concrete is ground to small pieces that are reused, and in this grinding process fines are also created. When treating these

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<sup>16</sup> A hydrogen strategy for a climate-neutral Europe, COM(2020) 301 final, Brussels, 8.7.2020

fines with CO<sub>2</sub>, 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 4 MtCO<sub>2</sub> are unlocked by this technology as well as a significant reduction in concrete waste.

Like the concrete fines, there are also other minerals that bind to CO<sub>2</sub> and CO, including naturally occurring minerals (e.g. olivine or serpentine). These minerals can be carbonated with emerging technologies to produce materials (e.g. precipitated calcium carbonate) 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 13 MtCO<sub>2</sub>, but the business case is to be further explored.

CO<sub>2</sub> curing of pre-cast concrete and the recycling of fines with CO<sub>2</sub> are in-factory processes, needing a CO<sub>2</sub>-rich 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.

#### 4.9 CO<sub>2</sub> and CO utilisation in chemicals and fuels

Captured CO<sub>2</sub> 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, as well as 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 ), which can be further transformed with the already available and new processes to other many other chemicals and fuels. The technologies could also produce fuels/chemicals directly as final products (without requiring the transformation of the chemical products listed below into fuels).

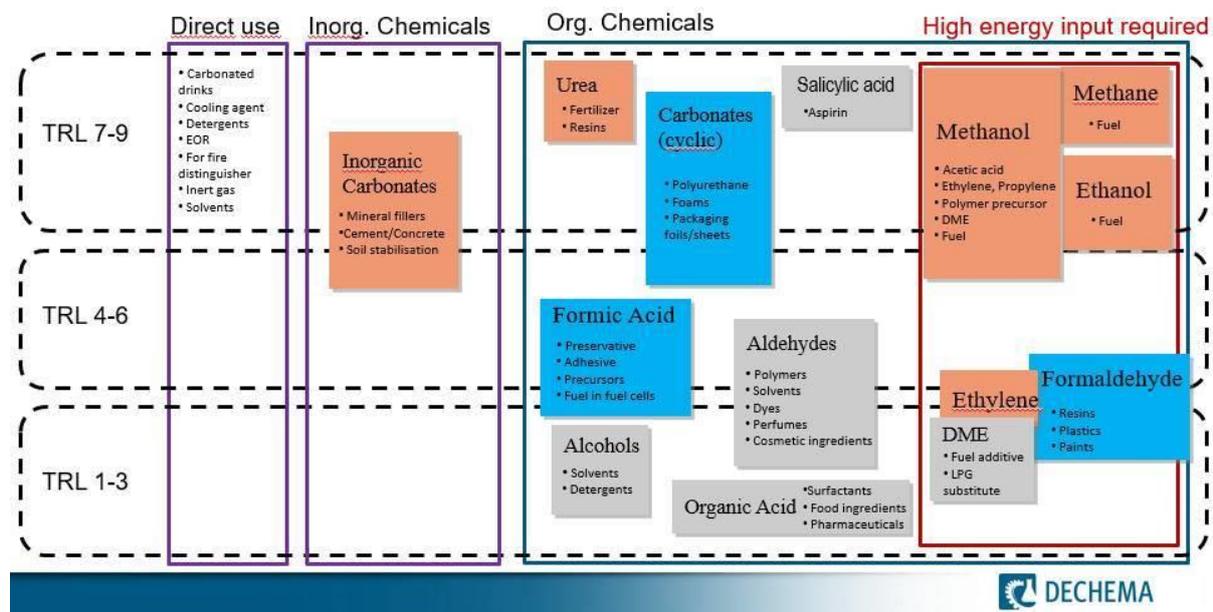


Figure 14: CO<sub>2</sub> utilisation routes towards chemical materials, and their status of development (DECHEMA, 2017)

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 (e.g. through plasma technology or electrochemistry), hydrogen or another chemical energy carrier to drive the reaction, together with a catalyst, that transforms CO<sub>2</sub> and other inputs like water into useful chemicals or fuels. Some of the technologies are already near commercial application. However, most technologies for **catalytic conversion of CO<sub>2</sub> to chemicals/fuels (A-8.b)** are at a lower level of maturity and require more development and demonstration in an integrated manner. It has the potential to reduce 134 MtCO<sub>2</sub> in 2050<sup>17</sup>.

Whereas some polymers can be produced based on CO<sub>2</sub>-derived building blocks (standard polymerization), the direct utilisation of CO<sub>2</sub> to produce some polymers can offer significant energy efficiency benefits. **Utilisation of CO<sub>2</sub> and CO as a building block in polymers (A-8.c)** is only possible for certain polymers where most of the CO<sub>2</sub> molecule remains intact and is integrated into the polymer. As a result, the CO<sub>2</sub> reduction potential is lower (around 1 MtCO<sub>2</sub>). The first pilots for such technologies are underway, and the aim is to be able to create polymers with 15% to 30% of CO<sub>2</sub> integrated in 2030 and 20% to 40% in 2050. The remainder of carbon feedstock can be delivered by other non-fossil sources. 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 (A-8.a)** technology<sup>18</sup> is still immature and not economical. A portfolio of projects for different technology options and integrated combinations will be developed until 2030 and the best technologies will be deployed post-2040.

Besides CO<sub>2</sub>, 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<sub>2</sub> take place, capturing these and using them often reduces overall GHG emissions and contributes to the transition. In a climate neutral 2050, however, fewer concentrated fossil CO/CO<sub>2</sub> emission sources will exist, and non-permanent CCU applications should be fed with either CO<sub>2</sub> from biomass, or with CO<sub>2</sub> from direct air capture.

#### **Text box 3: CCU's contribution to circularity**

The utilisation of CO<sub>2</sub> (and CO) as raw materials can contribute to GHG emission reduction and can play a key role in the transition to a more circular economy since it can effectively enable to recycle carbon from CO<sub>2</sub>.

Upon transition to a different feedstock mix, carbon for the process industries will have to come from CO/CO<sub>2</sub>, biomass or carbon already present in manufactured products such as plastics.

For all CCU technologies, standardised frameworks are required to compare technologies, ensure that the CO<sub>2</sub>-based technologies are carbon-negative as compared to the state-of-the-art and select the most promising ones for further development. Additionally, large quantities of affordable GHG emission-free energy are required.

## **4.10 Energy and resource efficiency**

Existing and new processes will benefit greatly from radically new processes with much higher energy efficiency and selectivity, producing less by-product/waste. This **breakthrough efficiency improvement (A-9.b)** will (among others) be delivered by process intensification and by developing processes that minimise non-recyclable waste, disruptively changing and

<sup>17</sup> Estimate based on (DECHEMA, 2017)

<sup>18</sup> It directly uses sunlight, CO<sub>2</sub> and water to produce chemical/materials, similar to how photosynthesis does this in nature

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 up to about 65 MtCO<sub>2</sub> emission reduction in 2050.

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 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.

To get these new processes going, and to enable many of the new technologies and reactions described in several other innovation areas, the 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. **Next-gen catalysts (A-9.a)** types are needed to deliver the energy required for reactions with new process technologies using electricity or direct solar radiation. By 2050 this is estimated to achieve 19 MtCO<sub>2</sub> emission reductions.

#### 4.11 Circularity of resources

Only 12% of the material resources used in the European process industry are currently recycled and recovered materials.

The “New Circular Action Plan for a cleaner and more competitive Europe”<sup>19</sup> underlines the broad range of required innovations to move further towards a truly circular economy: “Horizon Europe will support the development of indicators and data, novel materials and products, substitution and elimination of hazardous substances based on “safe by design” approach, circular business models, and new production and recycling technologies, including exploring the potential of chemical recycling, keeping in mind the role of digital tools to achieve circular objectives”.

The recently released “Chemicals Strategy for Sustainability” also insists on the need to ensure that “substances of concern [for human health and the environment] are minimised in products and recycled materials to move towards toxic-free material cycles and clean recycling.”<sup>20</sup>The Strategy mentions that “the Commission will support investments in sustainable innovations that can decontaminate waste streams, increase safe recycling”.

Processes4Planet will pursue a **wide variety of innovations** in order to drastically enhance the reuse and recycling of secondary resources and to reduce landfilling, while evolving towards a toxic-free environment.

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<sup>19</sup> Communication from the Commission, A New Circular Action Plan for a cleaner and more competitive Europe, COM(2020) 98 final, 11 March 2020

<sup>20</sup> Communication from the Commission, **Chemicals Strategy for Sustainability Towards a Toxic-Free Environment, COM(2020) 667 final**

The development of new sustainable-by-design materials (and their products) will aim at simultaneously optimising technical and ecological performance over the full life-cycle. The resulting **innovative materials of the process industry (A-10.a)** will – for example – have smartly extended lifetimes through in-situ (re-)functionalisation (examples: self-healing paint, self-repairing concrete).

Developing materials with better **inherent recyclability (A-10.b)** is also on the innovation agenda (expected not before 2030). The process industry has often optimised its materials towards maximum functionality for each application by ingeniously combining materials (multilayer plastics, composites, etc.). The recycling of these materials is often technically and economically challenging. It may be necessary to develop alternative materials to deliver the functionality currently provided by composites where there is no prospect of development of recycling technologies (outside the scope of this roadmap). Substances of concern for the environment and/or human health should also be minimized and substituted, as far as possible, in order to deliver a clean circular economy and to evolve towards a toxic-free environment.

Complementary to these programmes aiming at developing “sustainable-by-design” materials, breakthrough innovations are also pursued to **upgrade secondary resources (A-10.c)**:

- **A-10.c** separation, sorting and purification technologies, which combined with digital tools, will enable a robust processing of secondary resources with larger variations in composition/quality,
- other innovative technologies that enable recycling, either in the same sector or in other sectors. A wide variety of recycling options will be developed at enhanced scale.

#### **A-10.a**

**A-10.b** The next-gen catalysts, new (electrically driven) separation technologies and many other Several innovations [e.g. next-gen catalysts, new (electrically driven) separation technologies, energy recovery etc.] will also enable **wastewater valorisation (0)**. The strategy of water management is to increasingly move from wastewater treatment plants to water resource recovery facilities with increasing efficiency and affordably. This is achieved by improving separation technologies, increasing the valorisation of solutes and solids, optimizing the energy value in wastewater, developing new technologies to enable wastewater substituting freshwater and developing alternative processes using less water. This opens up the following potentials:

- **Recovering valuable nutrients**, inorganics and organics, as much as possible;
- **Eliminating hazardous inorganics and organics** which cannot be recovered:
  - Convert with reductive processes (such as anaerobic digestion towards energy carriers) in case that is not possible by oxidation;
  - Send to controlled incineration (for example, some sludges of physico-chemical treatment) in case that is not feasible;
  - Send to controlled landfilling;
  - Phase out;
- Extracting as much **energy** as possible from water and limit energy demand;
- **Reusing the water** and/or **prevent production of wastewater**;
- Using artificial intelligence and sensing to manage operations more efficiently, reliably, and remotely.

In order to deliver the step change we need in the circular use of resources, developing and validating innovative technologies is a necessary but not sufficient condition.

Waste policies are and will remain key enablers of successful prevention of landfilling and maximised use of secondary resources, as they notably define how our society collects, sorts and treats waste as well as the underlying financing mechanisms. Product standards and norms must also be adapted to enable or even encourage the safe and clean recycling of secondary resources.

Hubs for Circularity will also be important enablers in the optimisation of regional waste flows as they ambition to play a central role to facilitate the management of resources in their respective regions.

Other key success factors will also be reliable mappings of waste streams in each given region and knowledge sharing programmes on circularity enabling technologies and final applications.

#### 4.12 Industrial-urban symbiosis

*“Industrial(-Urban) Symbiosis is a system approach to identify business opportunities and 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 variety of technologies making it possible to:

- to process outgoing material flows from one company (purify, decontaminate, recycle etc.) and make them ready to be taken and used by another company;
- to control and balance the processes between the connected companies involved;
- to share necessary data without compromising the compliance requirements;
- to assess and share benefits among the parties involved;

etc. Figure

Demonstrating the technologies for **Industrial-Urban Symbiosis (I-US) (A-11.a)** and overcoming the non-technological barriers to their implementation are the aims of this innovation area. It is expected that 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. 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 I-US demonstration projects will focus on water, energy, CO<sub>2</sub>-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. The potential of I-US to reduce GHG emissions is estimated to be on the order of magnitude of 10% (i.e. about 50 MtCO<sub>2</sub>) and the potential to reduce waste is about 380 Mt in 2050.

#### 4.13 Circular regions

Section 3.4 presents the Hubs for Circularity and describes the need for support to promote the emergence of more H4C. Through this innovation programme the establishment and development of H4C is stimulated.

As confirmed by Klaus Sommer in his report on Industrial Symbiosis, well-organised facilitation is the basis to promote Industrial-Urban Symbiosis and circularity and drive their implementation.

One of the most important barriers to collaboration in general, and to the implementation of Industrial Symbiosis in particular, is indeed the building a long-term trust relationships.

Facilitators are neutral towards any of the participating organisations and are observing the common advantage created by all and a fair distribution of profits. They should also be well familiar with the regional specifics, with the technological state-of-the-art and with barriers to innovation to be able to effectively foster the design of innovative projects and involve the right stakeholders in the right way for the implementation of Industrial-Urban Symbiosis and Circularity. P4Planet will support the regions to become efficient H4Cs through:

- Providing an exchange platform for best practices;
- Providing a data base for evaluated tools, technologies and specific material flows with potential to become feedstocks for process industries, for or in collaboration with the regional facilitators;
- Providing help with a gap analysis for tools and technologies that need to be developed at high priority to help regions in the implementation of symbiotic and circular solutions;
- Promoting topics for HEU calls that will help to close the most impactful gaps.

Thanks to this facilitation, it will become more feasible for the regions to develop an innovation business plan for the territory and to implement co-financing models. The aim is to have sustainable and self-sustaining H4Cs, that will continuously drive the transition without dependence on time limited project-related funding.

P4Planet will support the creation of **Hubs for Circularity (H4C) (A-12.b)** and will aim at 15 mature H4Cs by 2030 and 50 H4Cs by 2050. Over the transition time, there will be multiple individual H4Cs at different maturity levels. The support by P4P will help those more mature to act as lighthouses for those in their early development and to widespread best practice across Europe.

In order to avoid fragmentation, a common platform for regional H4Cs for knowledge creation, best practice exchange and training will connect the Hubs on the EU level and use the synergies to accelerate the progress.

This EU-wide network of networks is called the **European Community of Practice (A-12.a)**. P4Planet will facilitate the formation of a small expert team that will manage the knowledge generated by the hubs. It will potentially lead to the formation of a European H4C association. Figure 5 illustrates how the European Community of Practice will coordinate the exchange of knowledge, tools and best practices to accelerate deployment of solutions towards climate neutrality, circular economy and competitiveness. Collaboration 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 will be actively pursued.

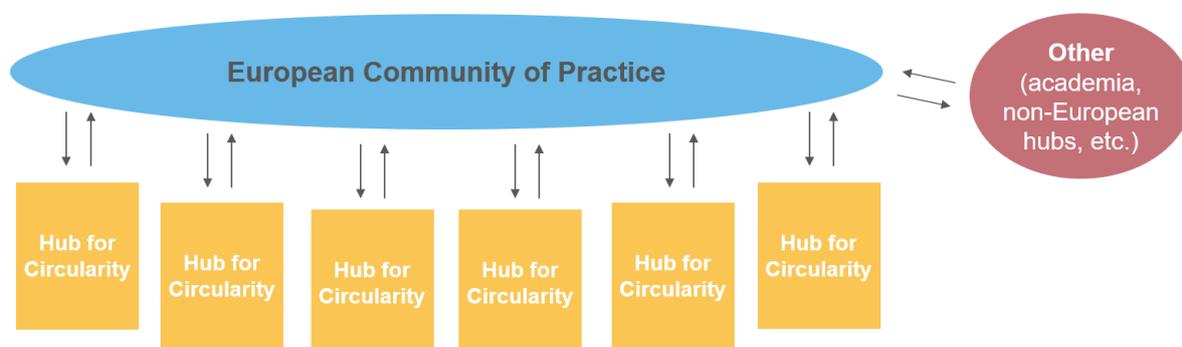


Figure 15: European Community of Practice – connecting hubs for circularity across the EU

P4Planet will also link the H4Cs via the community of Practice to other innovation programmes. Long term commitment, support and investments from the EU, 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.

#### 4.14 Digitalisation

The digitalisation of the process industries 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. It will make processing plants and operations more agile and resource and energy efficient, contribute to significant reductions of GHG emissions, orchestrate the pathway to a climate neutral economy, improve safety and working conditions and contribute to securing competitiveness and jobs in the European process industries over the next decades. The potential impact of digitalisation exceeds that of historic disruptive technological breakthroughs like the steam engine or automation (Larsson, 2019).

Digital technologies act as key enablers for various other innovations in this roadmap, 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.

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 (for example quantum computing).

##### Digitalisation of process/product R&D

Digital technologies will increasingly be applied in the different stages of product and process research and development. They will enable the integration of 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.

Technologies will be developed to enable **digital materials design (A-13.a)**. This includes the 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, and the development of digital tools for effective and intelligent data and knowledge management.

Materials and formulation design will be integrated with process design to achieve **digital process development and engineering (A-13.b)**. Information about the production process and the feedstock will be included into the materials design phase and detailed characterisation methods of (secondary) feedstocks will be developed 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.

### **Digitalisation of plants**

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<sub>2</sub>, CO<sub>2</sub>) and 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 and 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, resource efficiency and other relevant indicators such as the CO<sub>2</sub>-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, even among 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 solutions. 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.

Tools are needed for **digital plant operation (A-13.c)** 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 material and equipment monitoring (A-13.d)**, 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 are needed 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, 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 life cycle assessment aspects into the plant and sitewide monitoring strategies

### **Digitalisation** of connected processes and supply chains

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 the 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 (wastewater treatment, thermal treatment, other by-products, etc.) optimisation.

The first two levels can be supported by a set of digital solutions for **autonomous integrated supply chain management (A-13.e)**. 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:

- Development of solutions for integrated planning, scheduling and control within plants to optimise efficiency and reliability of supply while 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 and 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 life cycle assessment 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 Circularity of resources).
- Real-time characterisation of waste streams (see also Circularity of resources), enabling an increase of the use of secondary materials.

The third level, full supply chains, needs the development of digital technologies that enable **digitalisation of industrial-urban symbiosis (A-13.f)**.

Efficient industrial symbiosis requires a continuous adaptation of all parties involved in 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 not only industrial and urban-industrial water and waste-water treatment and distribution systems, but also 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. Ultimately digitalisation of the full value chain can be achieved, from the ingoing waste streams to their processing and the delivery of feedstock to the

process industries. This ensures 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.

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.
- **Organisations 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.
- **Foster technology transfer** from other sectors (e.g. consumer, military, construction, finance, tourism, etc.) back to the process industries.

#### 4.15 Non-technological aspects

All the innovations outlined in this chapter will only be successful if technological innovations are supported in their deployment by non-technological elements (such as skills, societal acceptance, or market conditions). In the modern mission-oriented innovation paradigm, a stronger recognition of non-technological aspects and of the added value of an open innovation processes are key<sup>21</sup>. If societal, economic and environmental contexts are properly taken into account and if resulting implementation challenges are addressed, technological innovations can deliver so much more societal, economic and market impact.

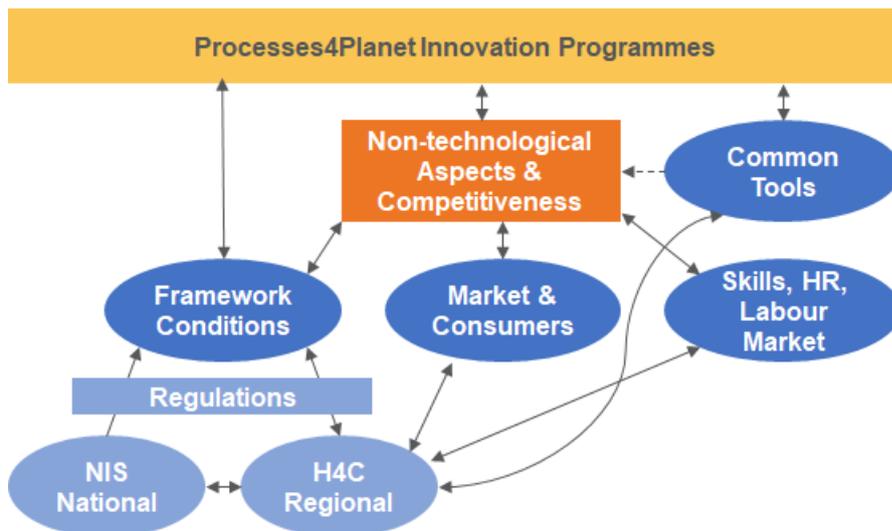
It is therefore important to open the innovation processes by co-creation, user and worker involvement, empowerment of citizens and cross-sector collaboration – considering economic, social, and environmental impacts as well as organisational and personnel development right from the beginning (“bringing technology into society”).

This holistic understanding of innovation affects all the innovation areas and programmes of P4Planet.

From a technological standpoint, P4Planet will notably aim at making technologies competitive. Similarly, from a non-technological standpoint, the main goal will be to improve technology development and boost implementation from a social innovation perspective. As such, when calls are formed, the necessary non-technological activities will be considered. An initial checklist for this process is included in Appendix A-14.a. The checklist builds on the conceptual framework for non-technological aspects depicted in Figure 116. For some innovation programmes, non-technological activities have already been defined.

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<sup>21</sup> See for example (Fraunhofer, 2018), (Mazzucato, 2018), (Howaldt, Schwarz, Henning, & Hees, 2010), or SPIRE project COCOP



**Figure 16: Conceptual framework for non-technological aspects relevant for the P4Planet innovation programmes**

The framework shows that four elements need to be considered for addressing the non-technological aspects. These aspects are all covered by the innovation areas.

**European, national and regional framework conditions** have several dimensions, including the value chain dimension and the regional dimension. On the global and European level, framework conditions include raw material prices, energy and waste regulations, cross-border issues, ETS and standardisation. This dimension is addressed by the innovation programme European Community of Practice (see A-12.a). On the national and regional levels, the National Innovation Systems (NIS) and other support and facilitating frameworks are considered in the H4C approach (see A-12.b). That also promotes involvement of the value chains, SMEs and innovative start-ups.

The **uptake and management of market and consumer demands** and changes, as well as the development of new social practices (e.g. environmentally responsible behaviour) will also be addressed by the H4C. They will integrate stakeholders from economy, science, policy and civil society to join competences, forces and responsibilities for changing social practices of the people (behaviour, acceptance, buying), in the companies/shop floor and society/region, interacting with regional development plans.

The development of **effective common tools** such as life cycle assessment, business models, new (digital) learning arrangements and methodologies (e.g. facilitators and governance, ecosystem approaches) will happen in the various innovation programmes, with the results collected and shared through the European Community of Practice (see A-12.a).

**Human resources, skills and labour market (A-14.b)** conditions are key to consider with respect to digitalisation and innovation within the companies and the regions. Skills and education are a bottleneck to develop, implement and unfold the full potential of new technological solutions within and across companies (e.g. industrial symbiosis). To bridge the gap between the fast-changing new skills demands of the companies and the available training and education support, new (digital) learning arrangements will be developed as well as a better connection to other European and national activities and programmes: EIT, Erasmus+, New Skills Agenda, Smart Specialisation Regions, Marie Curie Training Networks, Digital Innovation Hubs, Europe Enterprise Network, Pact for Skills and others. This includes the development and implementation of new job profiles, appropriate and short-term up- and reskilling schemes, new (digital and on the job) learning arrangements. This also includes recruiting and retaining

strategies aiming at attracting and keeping talented individuals in the process industries. These sectors will gain in innovation abilities (both at design and deployment stages) if they succeed to attract and retain a more diverse and/or high skilled workforce, attracting more women and overcoming demographic change. In particular, a better gender balance does boost innovation in companies, as demonstrated by several recent studies<sup>22</sup>. Making process industries more attractive for the younger generation is crucial to enhance deployment of digital technologies in these sectors.

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<sup>22</sup> [Getting to Equal 2019: Creating a Culture That Drives Innovation, Ellyn Shook and Julie Sweet, Accenture \(2020\)](#)

## 5 Synthesis

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The previous sections have explained the status quo, listed the innovation challenges and mapped the solution areas that contribute to delivering a climate neutral and circular industry in 2050. This section synthesises the roadmap while putting it in its general context.

It starts by referring to the general, specific and operational objectives of the P4Planet partnership, as outlined in the P4Planet Guidance Document.

It synthesises afterwards the roadmap itself and explains how the innovation portfolio helps achieve the P4Planet objectives and delivers impacts. It also lays out when the innovations are expected to be ready for deployment and summarizes the investment needs. Finally, the benefits of P4Planet's unique approach to innovation are explained.

### 5.1 P4Planet's objectives

The general, specific and operational objectives of the P4Planet partnership are presented in Figure 17 which shows their direct connection to the problems and problem drivers they respectively address, as well as to the Innovation Areas of the roadmap.

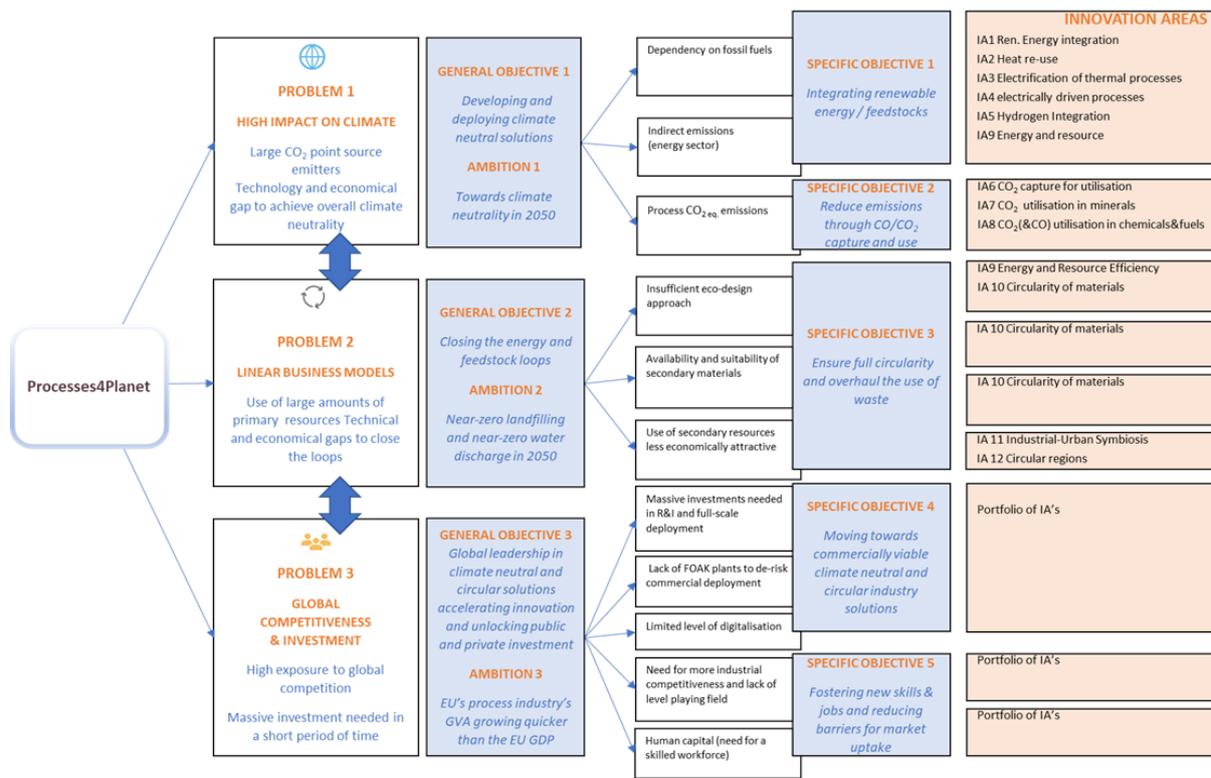


Figure 17: general, specific and operational objectives of the P4Planet partnership.

## 5.2 P4Planet’s innovation portfolio

The overview of the innovation programmes (Figure 12 and Figure ) in Section 4.1 already shows the many innovation areas where cross-sectorial solutions can be used across factory and sector boundaries to meet P4Planet’s ambitions of becoming climate neutral and circular while enhancing global competitiveness. When delivering the roadmap, it is key to innovate in an integrated fashion, rather than in the silos of respective innovation programmes. It is therefore crucial to coordinate innovation efforts across industry sectors.

Although innovations will be developed in a cross sectorial approach, a process specific adaptation and integration will be needed as well and demonstrated via the “Marbles”.

The **Hubs for Circularity** will serve as a key accelerator to bring stakeholders together, identify common problems and solve them in a collaborative manner. By a close connection to regional stakeholders within the H4C and co-investments, the innovation “valley of death” can be overcome and impactful innovations and technologies can be demonstrated and rolled out effectively across Europe.

The roadmap is fully aligned with the EU Green Deal objectives and other EU policies and roadmaps (notably the New Action Plan for a Circular Action Plan for a Cleaner and more Competitive Europe, the New EU Industrial Strategy and the Chemicals Strategy for Sustainability, see Appendix B for more details). The innovation portfolio will significantly

contribute to delivering progress towards the Sustainable Development Goals<sup>23</sup> and targets 4 out of 6 SDG transformations that are framed for the EU (SDSN & IEEP, 2019)<sup>24</sup>. All actions that are prioritised in SET plan Action 6<sup>25</sup> by member states and other stakeholders (SETIS, 2017) are covered in this roadmap, except for sector-specific technologies.

### 5.3 Impact on GHG and waste

The impacts of each innovation programme on GHG emissions, waste reduction and competitiveness are estimated where possible. Appendix A provides the detailed estimations and Appendix E describes the analytical approach. A key assumption that is made is that electricity is produced in a climate neutral fashion in 2050. Many projections (including those from the EC) expect the emission factor to decrease, but not reach zero in 2050. However, these projections do not achieve a climate neutral society in 2050, and therefore the 1.5 °C scenarios presented in the EU Long term strategy are used to inform the emission factor<sup>26</sup>. These scenarios have a similar ambition as P4Planet and show an emission factor of zero in 2050. Note that as electricity is a GHG emission-free energy carrier in the impact estimations, electrification is highly effective in lowering emissions. If the power sector does not become climate neutral, such impacts will not be achieved. As the ambition is set for 2050, we also use a carbon intensity of zero for electricity in 2030, anticipating the 2050 emission factor.

Impacts cannot simply be added up because many innovations overlap. For example, solar heat or hydrogen can be used to replace currently used natural gas in a thermal process. Developing different solutions in parallel enables selection of the most cost-effective option in a specific application or geography.

In aggregate, it can be concluded that if successfully developed, the innovations make it technically possible to reduce all CO<sub>2</sub> emissions: **the combination of technologies which will have to be implemented to achieve the climate neutrality ambition will vary from sector to sector, possibly from plant to plant. It is actually also the case for the ambition of circularity. Figure XXX and figure XXX illustrate the patchwork of innovations which will be required to achieve these two ambitions.**

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<sup>23</sup> Mainly SDG 6: Clean Water and Sanitation, SDG 9: Industry Innovation and Infrastructure, SDG 11: Sustainable Cities and Communities, SDG 12: Responsible Consumption and Production, SDG 13: Climate Action

<sup>24</sup> Namely: 1) Well-educated workforce and innovative economy, 3) A climate neutral and circular economy, 5) Sustainable cities and communities, and 6) Digital and other modern technologies for sustainable development

<sup>25</sup> Strategic Energy Technology Plan action 6: Continue efforts to make EU industry less energy intensive and more competitive

<sup>26</sup> [28/11/2018 - COM \(2018\) 773 - A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy](#)

## A patchwork of innovations to achieve climate neutrality

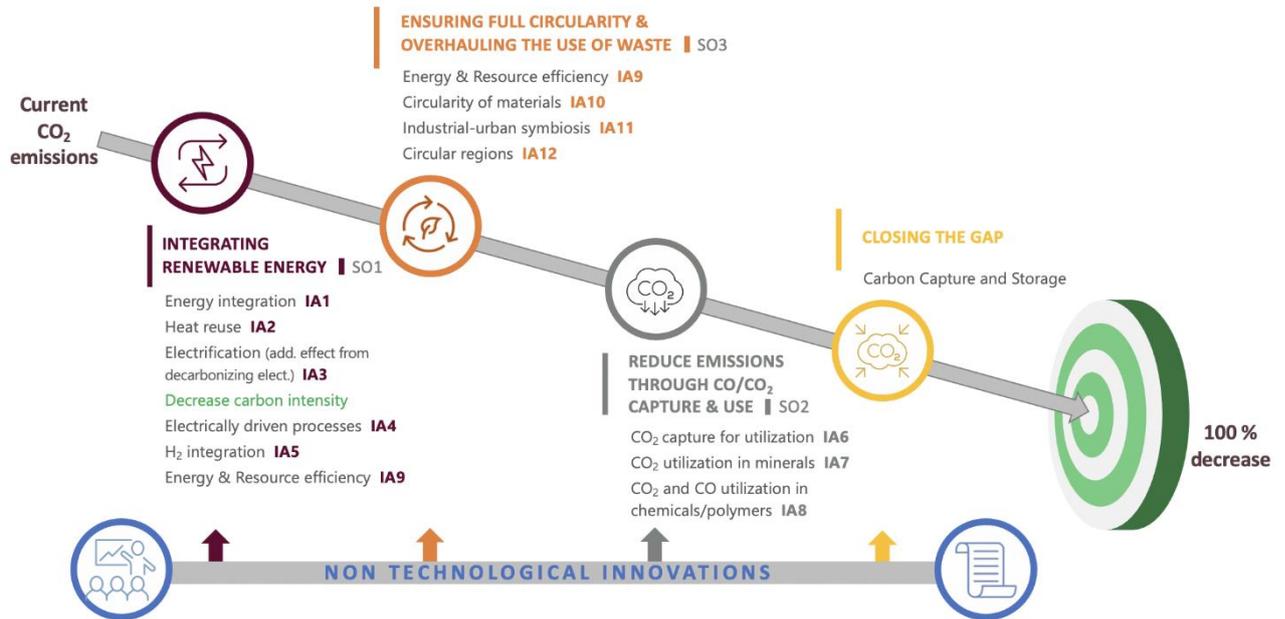


Figure XXX: the combination of technologies which will have to be implemented to achieve the climate neutrality ambition will vary from sector to sector, possibly from plant to plant

## A patchwork of innovations to achieve circularity

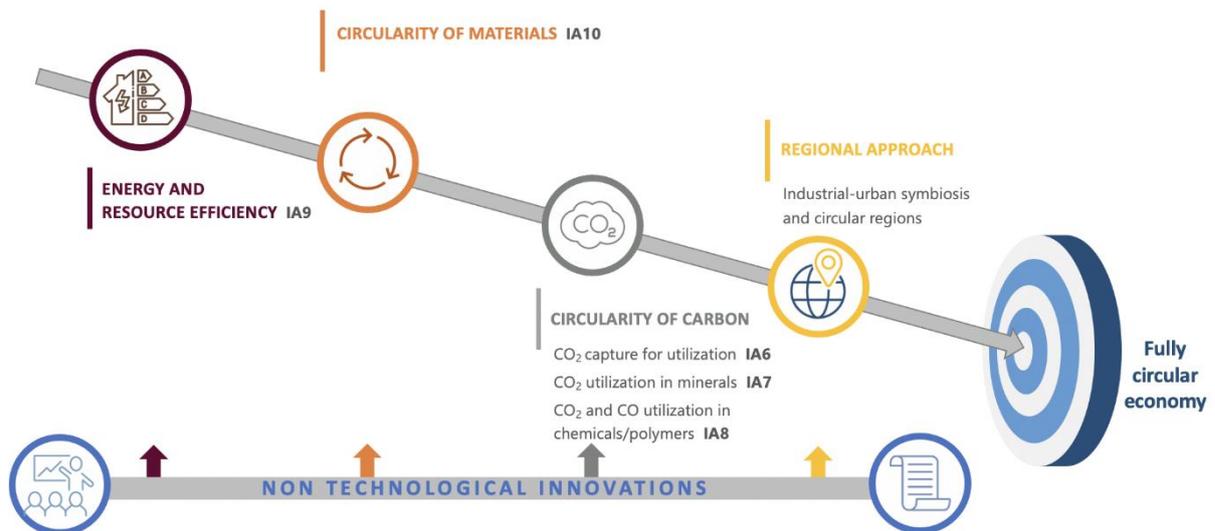


Figure XXX: the combination of technologies which will have to be implemented to achieve the circularity ambition will vary from sector to sector, possibly from plant to plant

All waste categories are considered in the roadmap, and the innovations should have the potential to significantly reduce landfilling. The programmed Coordinated Support Action should map the attainable reduction of landfilling further.

Circular process industries will play a crucial role to reduce pollution and achieve a toxic-free environment, both through innovation in “sustainable-by-design” materials and products and through innovation in recycling/reuse processes of secondary resources.

The rest of this section describes how the innovation in this roadmap enables each P4Planet sector to transform and contribute to the ambitions.

### 5.3.1 Cement

The cement sector can potentially reduce direct fuel related emissions (41 MtCO<sub>2</sub>) to a limited extent in 2030 by switching to alternative bioenergy and integrating renewable heat. After 2030, electrical heating of the cement kiln can be used as an alternative to bioenergy. Electrochemical options will also become available near 2050.

Carbon capture can be used to reduce remaining process emissions (61 MtCO<sub>2</sub>) in 2030. When applying oxyfuel processes, a pure CO<sub>2</sub>-stream can be produced that can be used as resource (CCU) for other materials, embedded for instance by mineralization, or stored. The potentials depend strongly on the geographic location.

In 2030, technology will be available that sequesters CO<sub>2</sub> in concrete fines from end-of life concrete, and simultaneously upcycles it for reuse as a building material. The CO<sub>2</sub> can come from any source, not just the cement sector. The cement sector is developing new cementitious materials that can replace clinker, hence the process emissions. Developing these new materials is outside the scope of P4Planet.

Avoiding landfilling of concrete by 2030 requires innovation in the recycling industry so that all individual components can be recycled at the highest value. Digitalisation of supply chains will support the tracking and tracing of materials.

### 5.3.2 Ceramics

Technologies to eliminate energy-related emissions (16 MtCO<sub>2</sub>) will emerge by 2030. The P4Planet portfolio will contribute to the abatement of fuel emissions by improving the process efficiency (including digitalisation for energy management and process optimization), recovery of excess heat with heat exchangers in the kilns stack or using biogas or integrated solar heat. After 2030, GHG emission-free hydrogen also becomes available. After 2030, electrification of kilns becomes possible for some applications, and in 2040 for the other applications. Integrated renewable heat can be used for drying purposes.

The process emissions (4 MtCO<sub>2</sub>) are dispersed sources of CO<sub>2</sub> with varying concentrations and volumes. In 2030, flexible CO<sub>2</sub> capture and purification technologies will be available to abate these emissions.

P4Planet aims at delivering process innovations to incorporate secondary resources, reducing the need for virgin materials. Smarter design of products and processes can result in easier-to-recycle and thinner products that use less material after 2030 (Almeida, 2016).

### 5.3.3 Chemicals

Direct emissions from the chemical sector can already be decreased in many ways in 2030. The indirect emissions can be reduced by using GHG emission-free electricity (54 MtCO<sub>2</sub>). To stimulate this, the sector can integrate renewable electricity or increase energy flexibility.

Natural gas can be replaced by biomethane in 2030 for thermal processes and electricity can be used to generate lower-temperature heat with heat pumps, replacing gas boilers (reducing 1 MtCO<sub>2</sub> in 2030). Energy efficiency improvements due to new catalysts, process intensification,

and digitalisation can reduce emissions further and make the chemicals industry more competitive, as can hybrid burners.

After 2030, GHG emission-free hydrogen can be used to substitute grey hydrogen, which production results today in the release of 70 to 100 Mt CO<sub>2</sub> annually in the EU ; and to substitute fossil fuels, reducing emissions by 31 MtCO<sub>2</sub>. In 2030, electric crackers become available as an alternative to reduce 31 MtCO<sub>2</sub> of emissions.

In 2050, CO<sub>2</sub> and CO can be utilized to produce building blocks for polymers, chemicals and fuels. Electricity or hydrogen can be used for this, with potential GHG reductions exceeding 100 MtCO<sub>2</sub> for the chemicals sector. Some chemicals can already be produced from CO from the steel sector in 2030. Alternatively, sunlight can be directly used with captured CO<sub>2</sub> (either from a point source or from the atmosphere).

It will be increasingly possible to recycle waste back into the chemical sector (e.g. plastics, used oils and solvents, etc.) with a wide variety of chemical recycling technologies that are being developed with the potential to drastically increase chemical recycling. The extent of the impact cannot be estimated yet. An in-depth assessment is programmed before 2024 to improve the knowledge about waste streams.

#### 5.3.4 Non-ferrous metals

Moving to GHG emission-free electricity will reduce most emissions (20 MtCO<sub>2</sub>). The P4Planet innovation enables integration of renewable electricity and enhancing energy flexibility to support this development. The remaining direct emissions stem from the use of carbon electrodes, carbon reduction agents and fuel for heating purposes. Process CO<sub>2</sub> emissions (5 MtCO<sub>2</sub>) can be abated by applying inert cathodes or bio coal cathodes. Fossil fuel emissions (10 MtCO<sub>2</sub>) can be reduced by improving energy efficiency and using biomethane. All these innovations can take place before 2030. After 2030, GHG emission-free hydrogen can be used to substitute natural gas and after 2040 electrification of heaters becomes possible.

Design for recycling is needed to increase the recovery rate of non-ferrous metals, especially composites. P4Planet innovations aim for efficient and climate friendly recovery and recycling of metals, digitalisation of the value chain, inherent recycling of materials and establishing new recycle value chains where they do not exist yet. This is expected in 2040.

#### 5.3.5 Steel

By 2030 bio coal and hydrogen can be used to substitute fossil coal in the existing integrated steel production, reducing 30% of emissions in the BF/BOF route. If 10% of steel plants would deploy this technology between 2024 and 2030, then in 2030 this would have an impact of 5 MtCO<sub>2</sub>, not considering the economics. Digitalisation of the plants can support to increase the process efficiency, e.g. by reducing the number of cooling and heating cycles of finished products. The emissions of secondary steel making can be eliminated by applying GHG emission-free electricity for the indirect emissions, and bio coal for the anodes.

Furthermore, the blast furnace gases (CO and H<sub>2</sub>) can be used in the chemical industry to produce chemical products or synthetic fuels by 2030.

After 2030, hydrogen-based DRI enables GHG emission-free steelmaking that can eliminate the full 190 MtCO<sub>2</sub> of direct emissions in 2050 when combined with biogas. Alternatively, new iron making technologies, based on iron bath smelting, create pure CO<sub>2</sub> streams that can be used as secondary resources or combined with CCS. Renewable energy (biogas and electricity) can be used for finishing and other smaller operations. The elimination of preparation processes like coke making and sintering when switching from coal will reduce onsite waste production significantly, reducing the need for handling these streams. The emissions related to downstream steel processing still need to be eliminated using steel sector-specific innovations.

Sophisticated recycling technologies will be developed before 2040 that clean the scrap from other elements, notably non-ferrous metals. These metals can be recycled and used as secondary resources. The steel scrap of high purity can be melted in an electric arc furnace.

### 5.3.6 Minerals

Direct emissions from the minerals sector mainly arise from lime kilns. All direct fuel related emissions (6 MtCO<sub>2</sub>) can be eliminated by 2030 by switching to bioenergy and after 2030 through the integration of renewable electricity or heat. Carbon capture can reduce process emissions (14 MtCO<sub>2</sub>) in 2030. Oxyfuel processes can be applied to create a pure stream of CO<sub>2</sub> that requires less purification. After 2030, electrical heating of the kiln can be used as an alternative to bioenergy. Near 2050, electrochemical options that also produce hydrogen will become available and will require integration. All CO<sub>2</sub> emissions can be reduced in 2050 with these technologies.

The indirect emissions (3 MtCO<sub>2</sub>) from electricity consumption (largely due to the mining of industrial minerals) will be reduced as GHG emission-free electricity becomes available. The direct integration of renewable electricity of heat and energy flexibility can support the power system transition.

### 5.3.7 Water

The water sector can reduce its indirect emissions from used electricity (6 MtCO<sub>2</sub>) through energy efficiency and use of renewable energy (either integrated or from the grid) and can also generate more renewable energy (e.g. biogas through anaerobic digestion) that can reduce emissions elsewhere.

The increased valorisation of more components can significantly reduce the amount of landfilled / incinerated sludge. Over time, more and more technologies will be developed to enable this valorisation.

### 5.3.8 Pulp and Paper

Direct carbon emissions of the pulp and paper industry (31 MtCO<sub>2</sub>) are almost entirely derived from combustion of fossil fuels, with natural gas being responsible for about ¾ of total emissions.

In moving forward, priority is to continue investing in energy and resource efficiency, to reduce the amount of energy needed. Until 2030 up to 2.5 MtCO<sub>2</sub> can be obtained with digitalisation and process innovations, e.g. reducing the amount of water to be evaporated and upgrading exhaust vapour as to allow effective use of heat pumps.

Secondly, an important role could be played by on-site, or nearly on-site, renewable energy sources. Solar thermal, geothermal, on-site biogas production, are all useful tools to partially reduce the demand for energy to be delivered via energy infrastructures to the paper mills (up to 15 MtonCO<sub>2</sub> reduced).

Strengthening local partnerships for the direct use of biogas locally produced, before being upgraded to biomethane, would also be a cost-effective and resource-efficient solution to both reduce carbon emissions in the sector and support local communities.

Direct use of electricity could also be an option, but electricity prices would have to be cost-competitive and/or electro-technologies would have to deliver sufficient energy savings to offset the increased cost per unit of energy consumed.

Biomass represents already 60% of the fuels used in the pulp and paper industry. Further increase of biomass sourced from sustainably managed forests is possible, although several factors act as a barrier for fully exploiting the potentials of this option (inter alia: limited to no access to biomass feedstock, lack of public acceptance by local communities, lack of storage facilities, logistics constraints).

Biomass also represents an opportunity for the sector, as it is primarily a raw material that can be further valorised for replacing fossil-based or carbon-intensive products in several downstream activities, especially when with new pulping processes higher energy efficiencies are obtained.

After 2030 more radical innovations may lead to significant emission reduction, like paper making without water or without water evaporation. Innovative energy efficient pulping processes will enhance indirect emission savings in the chemical industry as wood components currently used as CO<sub>2</sub> neutral energy source may than be used to replace fossil based feedstock.

### 5.3.9 Refining

The development and scale-up of the key CO<sub>2</sub> mitigation and alternative feedstock related technologies in the 2020-2030 timeframe, in a highly competitive international environment, is one of the main requirements (and challenges) to enable the successful transition of the refining sector. As a first step, the development of CO<sub>2</sub> efficiency technologies (energy efficiency, use of low carbon energy sources and carbon capture and storage as described in chapter 3.9) could enable to abate up to ~70% of the direct and indirect refining related emissions by 2050. The progressive replacement of petroleum by alternative bio/waste feedstocks could offer additional GHG reductions for the site beyond 90% (with the potential to achieve even negative emissions in future bioenergy schemes coupled with carbon capture and utilisation/storage). As an estimate, the production of low-GHG intensive products will require an estimate of €30-40 billion investment for the refining industry over the next ten years with the first-of-a-kind biomass-to-liquid and CO<sub>2</sub> valorisation (into fuels) plants coming into operation in that period. The level of investment estimate for the whole transformation of the refining system is well above 500 billion € with the potential to cut over 400 Mt CO<sub>2</sub>/y by 2050. To achieve so, maximising synergies among sectors for the development and scale-up of the key low GHG technologies identified in Process4Planet, integrated in highly digitalised energy and industrial hubs, are some of the key enablers which will allow the transition to a climate neutral society.

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The P4Planet innovation portfolio will improve the competitiveness of the process industry compared to a scenario in which the ambitions (contribute to climate neutrality, near-zero landfilling, and near-zero wastewater discharge) would need to be delivered without these innovations because:

- New energy efficiency measures become available, reducing energy costs. This is achieved through for example digitalisation (A-13.c), next-gen catalysts (A-9.a) and advanced heat reuse (A-2.a).
- 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) and shifting value from industries producing primary resources (e.g. iron ore or naphtha) to the process industries, provided the process industries seize this opportunity.
- The increased technology options developed under P4Planet allow the selection of the best-fitting and least-cost option for each specific application and situation. For example, biomass can be competitive at low enough prices combined with a carbon price (A-1.b), electric boilers can be competitive when electricity prices are low enough for part of the time (A-1.c, enabled by digital optimisation tools; A-13.e) and alternative hydrogen routes become competitive under different conditions (A-5.a). For CO<sub>2</sub> capture, cost reductions of 32% are aimed for in 2050 (A-6.a).
- 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 (A-12.b).
- Cross sectorial sharing of learnings accelerates the innovation speed and reduces innovation costs. The learnings and innovations can also become an export product: European cleantech can transform process industries globally, led by the engineering sector.

## 5.4 Milestones

Table 2 provides an overview of the progress of each innovation programme. It shows what share of the total TRL9 projects in that innovation programme are ready at the milestone year (and for programmes without TRL9 projects the % of investment needs).

In total, 463 TRL9 projects are included in the portfolio. This is substantially higher than the 180 projects that Roman Doubrava from DG CLIMA had included in his inventory for the Innovation Fund (as he mentioned during the stakeholder event). This difference makes sense as the programmed TRL9 projects are determined based on what is needed towards 2050, and not based on what is already in the pipeline. As such, several technologies need to be developed from TRL1 onwards. Additionally, in practice multiple TRL9 technology demonstrations can be combined in a single large project (hence the concept of the marbles). Therefore, the number of TRL9 projects is considered to be in the right order of magnitude.

Table 2 shows that several innovation programmes aim to deliver technologies ready for deployment by 2024. Most of the innovation programmes have technologies ready for deployment by 2030. Only artificial photosynthesis is not expected to deliver any commercial technologies at that time. The reason for this is that this technology is less mature and requires more development. In 2040, most technologies are ready for deployment, and in 2050 all technologies in the roadmap are fully developed. Note that this analysis does not consider market readiness or commercial readiness levels.

**Table 2: Progress of innovation programmes over time**

Innovation Area	Innovation programme	2024	2030	2040	2050
<b>Renewable energy integration</b>	1a - Integration of renewable heat and electricity	32%	100%	100%	100%
	1b - Integration of bioenergy, biomass/waste, and other new fuels	0%	60%	100%	100%
	1c - Hybrid fuel transition technologies	38%	100%	100%	100%
	1d - Flexibility and demand response	25%	75%	100%	100%
<b>Heat reuse</b>	2a - Advanced heat reuse	13%	38%	100%	100%

Innovation Area	Innovation programme	2024	2030	2040	2050
<b>Electrification of thermal processes</b>	3a - Heat pumps	15%	54%	100%	100%
	3b - Electricity-based heating technologies	0%	38%	100%	100%
<b>Electrically driven processes</b>	4a - Electrochemical conversion	0%	31%	100%	100%
	4b - Electrically driven separation	0%	60%	100%	100%
<b>Hydrogen integration</b>	5a - Alternative hydrogen production routes	25%	38%	75%	100%
	5b - Using hydrogen in industrial processes	11%	67%	100%	100%
	5c - Hydrogen storage	0%	75%	100%	100%
<b>CO<sub>2</sub> capture for utilisation</b>	6a - Flexible CO <sub>2</sub> capture and purification technologies	15%	54%	85%	100%
<b>CO<sub>2</sub> utilisation in minerals</b>	7a - CO <sub>2</sub> utilisation in concrete production	0%	50%	100%	100%
	7b - CO <sub>2</sub> and CO mineralisation to produce building materials	0%	50%	100%	100%
<b>CO<sub>2</sub> &amp; CO utilisation in chemicals and fuels</b>	8a - Artificial photosynthesis	0%	0%	50%	100%
	8b - Catalytic conversion of CO <sub>2</sub> to chemicals/fuels	0%	13%	47%	100%
	8c - Utilisation of CO <sub>2</sub> and CO as a building block in polymers	0%	25%	63%	100%
	8d - Utilisation of CO to chemicals or fuels	0%	100%	100%	100%
<b>Energy and resource efficiency</b>	9a - Next-gen catalysis	10%	29%	81%	100%
	9b - Breakthrough efficiency improvement	14%	49%	100%	100%
<b>Circularity of materials</b>	10a - Innovative materials of the process industries	0%	25%	75%	100%
	10b - Inherent recyclability of materials	0%	25%	75%	100%
	10c - Upgrading secondary resources	5%	30%	98%	100%
	10d - Wastewater valorisation	26%	44%	91%	100%
<b>Industrial-Urban symbiosis</b>	11a - Demonstration of Industrial-Urban Symbiosis	0%	67%	100%	100%
<b>Circular regions</b>	12a - European Community of Practice	33%	50%	75%	100%
	12b - Development of Hubs for Circularity	16%	34%	72%	100%
<b>Digitalisation</b>	13a - Digital materials design	18%	100%	100%	100%
	13b - Digital process development and engineering	25%	100%	100%	100%
	13c - Digital plant operation	58%	100%	100%	100%
	13d - Intelligent material and equipment monitoring	73%	100%	100%	100%
	13e - Autonomous integrated supply chain management	32%	100%	100%	100%
	13f - Digitalisation of industrial-urban symbiosis	64%	100%	100%	100%
<b>Non-technological aspects</b>	14a - Integration of non-technological aspects in calls	Integrated in other programmes			
	14b - Human resources, skills, and labour market	29%	52%	76%	100%

\* Progress is depicted here as % of total TRL9 projects programmed in each programme, and for programmes without TRL9 projects (i.e. those in circular regions, digitalisation, and non-technological aspects) % of total programme funding until 2050 is used

In 2024, the innovation programmes will be evaluated, individually and collectively, to potentially adjust based on developments and steer towards reaching the ambitions.

## 5.5 Demonstrating Impact through the marbles

**A.SPIRE members have indicated their intention to invest in marbles to bring them to TRL9**, confirming a market pull for the innovations and the relevance of this roadmap. A marble is the first of a kind (FOAK) large scale build-up of one or more new technologies, integrated in its value chain, deployed by leading companies of the Process Industry. The marbles demonstrate the impact of the overall P4Planet program. The initial set of marbles identified and listed in table 3 is already covering the overall set of Innovation areas and programs defined in the 2050 roadmap showing the coherence of the P4Planet roadmap with industry priorities. It will be a showcase to the society and the related industries that the demonstrated new technological concepts are technically and economically feasible and leads to the expected impact at the level of climate neutrality and/or circularity.

All these projects tap on advances of 1 or more Innovation programs reaching TRL7 in time to realise large scale units.

Number	Sectors	Description	Timing demo	Budget large scale	Timing large scale
M1	Refining	Electric heaters (small-medium)	2023-2025	30	2025-2030
M2	Chemicals	Electrified Cracking (e-Cracker)	2023-2027	200-300	2027-2031
M3	Refining	Green H2 (Electrolyser)	2023-2025	70	2025-2030
M4	Chemicals	Methane Pyrolysis	2023-2027	100-200	2027-2031
M5	Refining	CCUS (refining sector) - CO2 capture - Amines		500	2025-2030
M6	Chemicals	Sustainable access to CO2	2024-2030	2x25-50	2024-2030
M7	Refining	CCUS (refining, power or other sectors) - CO2 capture - Chilled ammonia, polymeric membranes, solid sorbents, CF2 technology		?	2025-2030
M8	Refining	CCUS (refining, power or other sectors) - CO2 capture - Ionic liquids, biphasic solvents, encapsulated solvents, fuel cell, oxygen transport membranes, catalytic membrane reactor			2035-2040
M9	Chemicals	Direct CO2 to Polymers	2020-2030	4x100-150	2025-2035
M10	Chemicals	CO2 to C1 (CO,	2020-2030	4x100-150	2025-2035

		Methanol) and CN+1			
M11	Refining	E-methanol	2020-2025	70	2025-2030
M12	Refining	E-fuels	2020-2025	500	2025-2030
M13	Chemicals	Photo-electrochemistry for CO2 to C1 and Cn+1 Target Molecules	2024-2030	2x100-200	2030-2050
M14	Refining	Pyrolysis oil		100	2025-2030
M15	Refining	BTL / Waste-to-fuels		1100	2025-2030
M16	Chemicals	Pyrolysis to oil, naphta	2020-2024	3x150-250	2025-2030
M17	Chemicals	Pyrolysis of Polymers to High Value Molecules	2020-2024	3x150-250	2030-2050
M18	Chemicals	Plasma Technologies for Waste Valorisation (Plastic-to-Syngas)	2020-2024	200-300	2025-2030
M19	Chemicals	Gasification to Syngas, Methanol	2020-2024	2x150-250	2025-2030
M20	Chemicals	Solvolysis - Depolymerisation of Pure Plastic Waste Streams into Monomers	2020-2024	3x150-250	2025-2030
M21	Chemicals	Depolymerisation of Medium Pure Plastics Waste Streams to Monomers	2020-2024	3x200	2025-2030
M22	Chemicals	Depolymerisation of Medium Pure Plastics Waste Streams to Monomers via Biotech Processes	2025-2030	150-250	2030-2050
M23	Chemicals	Tracking and Tracing of Polymers	2020-2024	4x25	2020-2025

		Streams across Value Chains with Distributed Ledger Technologies			
M24	Chemicals	Electrochemistry for CO2 to CO	2025-2030	100-200	2030-2040
M25	Cement / Lime / Ceramics	CO2 Capture, purification and re-carbonation of concrete and clay based products	2020-2030		
M26	Cement / Lime / Ceramics	CO2 Capture, purification, utilisation and further sequestration (ex: recovery of exhaust gases to capture carbon)	2020-2030		
M27	Cement	Climate change solutions based on local symbiosis (Aalborg)		1150	2022-2030
M28	Cement	RECO2MED (CO2 Capture-Mediterranean project) follow up		160	2021-2028
M29	Cement (chemicals?)	Project WESTKUSTE 100 (oxyfuel process in cement plant)		200	2020-2025
M30	Cement / Ceramics / Lime	Power to Methane (CCU, H2 and methane production)	2030-2050		
M31	Cement / Lime	Performance based specs to low Carbon	2025-2030	20	2024-2030

		and CE concrete structures			
M32	Minerals / Ceramics	CO2 Capture, purification and use (using Calcium-based mineral via the Accelerated Carbonation).	2020-2030		
M33	Minerals / Ceramics	New era for electrical & electrochemical processes Should include indirect electrical input and other renewable energies into renewable thermal processes	2020-2030		
M34	Minerals / Ceramics	Heat Exchangers of the future. Key technologies to increase flexibility into energy mix	2020-2030		
M35	Lime / Ceramics	CCUS-ready CO2 in thermal mineral processing - Ceramics production - Electric kilns	2030-2050		
M36	Lime / Ceramics	CCUS-ready CO2 in thermal mineral processing - Ceramics production Solar kilns	2030-2050		

M37	Steel	Digital assisted scrap classification and sorting	2020-2024	2x 40	2024-2030
M38	Steel	Separation of dust phases	2020-2024	2x40	2024-2030
M39	Steel	Grid stabilizing and sector coupling by hybrid processes	2020 -2030	4x100	2030-2040
M40	Steel	Steel mill gas to polymer		2x 200-250	
M41	Steel	Steel mill gas to naphta		1x 250	2026 -
M42	Steel	Steel mill gas into NH3/urea		1x 275	2028 -
M43	Steel	High temperature heat recovery from slab/slag		2x 75	2025 -
M44	Steel	Towards closed loop water steelmaking		2x 50	2026 -
M45	Steel	Carbon2Chem	2016-2020	200-400	2025-
M46	Steel	Recycling of CO2 to CO	2021-2025	45-55	2025-2030
M48	Steel / Ceramics	Biomass and Biowaste as renewal energy - Torrefaction of biomass	2020-2030		
M49	Steel	Inductive product heating	2021-2024	90-110	2024-2030
M50	Steel / Ceramics	Flexible hybrid heating and treatment systems (e.g. Microwave assisted gas firing)	2020-2030	?	?
M51	Steel	Alternative high power heating	2021-2025	2x 270-330	2024-2030

M52	Steel	Slag phases recovery	2021 -2024	4x 40	2024-2030
M53	Steel	Membrane off-gas separation	2021-2025	90-110	2025-2030
M54	Aluminium (Alumina)	Moving to GHG-free alumina production : 1) Bayer Process - use of green energy in the digestion and evaporation processes, e.g using renewable electricity in high pressure electric boiler (e.g. 30 MW) or using solar energy/ renewable electricity for generating thermal energy which is stored, e.g via molten salts - 2) Calcination - Use of green fuels (e.g. Hydrogen) and/or electric/solar furnaces	2025-2030	100+	2030-2040
M55	Aluminium (Primary)	Enabling the use of renewable electricity (i.e. fluctuating energy input) in smelters by increasing thermal stability of the	2020-2025	50+	2025-2030

		electrolysis cells (including heat recovery) - On-going development and step-improvements			
M56	Aluminium (Primary)	Use of Inert anodes or green carbon sourcing for anodes used in smelters	2025-2030	100+	2030-2035
M57	Aluminium (Primary)	Fully optimised electrolysis cell including affordable measurement equipment for maximising anode efficiency (reduction of CO2 emissions) and for fully eliminating PFC emission, e.g. via optimised cell design and equipment and by using digital twins/modelling for optimal operation	2025-2030	100+	2030-2035
M58	Aluminium (Primary & Alumina)	Reduction of CO2 sources (maximising anode efficiency) and/or concentrate, capture & purification	2025-2035	100+	2030-2040

		CO2 from aluminium smelters or alumina refineries and use it for other purposes			
M59	Aluminium/ Ceramics	Substitution of natural gas by green fuels (e.g. Hydrogen) or/and using electric kilns instead of Natural gas-based kilns (integrated use of hydrogen)	2030-2050		
M60	Aluminium	Recovery and use of fatal/waste energy (gas/water) from lower temperature (e.g. coating lines, heating furnaces, hot fumes, etc.) especially in plants integrating various parts of the value chain	2025-2030	100	2025-2036
M61	Aluminium	Maximising Aluminium post-consumer scrap quality through optimised product design, better collection and preparation phase possibly	2023-2028	50+	2025-2035

		including sorting per alloy family through digitalisation and robotics			
M62	Water	New Electrical separation tech to extract new solutes from WWTP (Incl. Integration of elec., chemical, biotech) and new plant set up for utilisation of secondary materials		100+	2027-2030
M63	Water	Energy recovery in WW & sludges. Incl. Recuperation of organics for methanisation and heat exchange for energy efficiency		100+	2027-2030
M64	Ceramics	Digital Transformation of Construction Products - Digital barcodes to enable product passports: Circular Economy, H4C, etc.	2020-2030		
M65	Ceramics	Re-use of waste into secondary materials	2020-2030		

M66	Ceramics	Climate change solutions based on local industrial/regional symbiosis - Tracking and Tracing end-of-life Ceramic products across Value Chains	2020-2030		
M67	Ceramics	Reforestation as mean to make carbon sources, in collaboration with PI	2020-2030		
M68	Ceramics	Full production line for ceramics tiles and/or bricks switching from high temperature thermal processes to low CO2 emission processes	2020-2030		
M69	Ceramics	Systemic solutions for urban waste water (reclaimed water) use into the process industry	2020-2030		
M70	Ceramics	Industrial deployment of condensation and gas purification systems for water recovery and	2020-2030		

		re-use in the process industry			
M71	Ceramics	Development of a conditioning plant for the adaptation of waste converting it into by-products for the ceramic sector	2030-2050		
M72	Ceramics	Fully digitalised production plant to optimize resource consumption (water, energy, raw materials...) in a systemic way	2030-2050		
M73	Ceramics	Demonstration of heat exchangers in corrosive gaseous flows	2020-2030		
M74	Ceramics	Integration of high temperature heat pumps	2020-2030		
M75	Ceramics	Systems for electric energy generation from waste heat	2020-2030		
M76	Ceramics	Thermal energy storage systems (i.e., recovering heat, storing it, and using it when it is needed, either as heat	2020-2030		

		or converting it to electrical)			
M78	Ceramics	Renewable electricity for drying process	2030-2050		2030-2035
M79	Ceramics	Solar thermal for drying process	2030-2050		2030-2035
M80	Ceramics	High temperature heat pumps for the drying process coupled with renewable electricity	2030-2050		2030-2035
M81	Ceramics	Microwave heating for the drying process coupled with renewable electricity	2030-2050		2030-2040
M82	Ceramics	Store and later use the waste heat for the drying process	2030-2050		2030-2035
M83	Ceramics	Platform (at semi-industrial scale) to evaluate the technical and economic potential of new climate neutral solutions for drying and firing ceramics.	2020-2030		2025-2030
M84	Ceramics	Sustainable manufacturing process of porcelain stoneware ceramic tiles based on	2020-2030		2026-2027

		ceramic body dry preparation			
M85	Ceramics	Water and energy save in ceramic tile spray-drying process through recovering and reusing of water evaporated in spray drying step of the ceramic process, for the preparation of slurries	2020-2030		2025-2027
M86	Ceramics	Hydrogen and oxygen production in the installation by hydrolysis powered by renewable energy for self-consumption (green hydrogen);	2020-2030		
M87	Ceramics	High-temperature gasification of wastes to produce a synthetic gaseous fuel as substitute for natural gas	2020-2030		

**Table 3: List of marbles of the P4Planet sectors scheduled for launch and deployment in the period 2021-2030;**

## 5.6 Investment needs

Table 43 summarises the estimated investments required for all innovation programmes.

Appendix E-5 provides more details about how the investment needs are estimated. Investment needs include the total investments of the project (CAPEX for the innovative parts and costs of testing, including materials etc.). Investments required for the deployment of the technologies are excluded from this table. The total investments needed are estimated to be €33.8 billion until 2050.

**Table 43 Total required investments for all P4Planet innovation programmes in € million<sup>27</sup>**

Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
2020-2024	€1,692	€2,749	€2,448	€1,300	€111	€8,299
2024-2030	€295	€1,372	€3,338	€6,488	€47	€11,539
2030-2040	€228	€450	€1,515	€9,040	€83	€11,316
2040-2050	€300	€500	€500	€2,430	€64	€3,794
<b>Total</b>	<b>€2,515</b>	<b>€5,071</b>	<b>€7,801</b>	<b>€19,258</b>	<b>€305</b>	<b>€34,948</b>

The estimated investments are highest in the first decade (€19.8 billion), as most innovation is frontloaded to maximise GHG reduction impact. Investments needed decrease in the second decade (€11.3 billion) and third decade (€2.6 billion).

The investment needs are substantial, but they are in the order of magnitude where they can be expected based on other studies. The market testing study for the innovation fund provided an indicative estimation of the investment volume required for demonstration projects (TRL5-8) in energy-intensive industries (including industrial CCS and CCU) of €31-42 billion (EC, 2019c). This number has a broader scope since it also includes CCS and sector-specific technologies, but it is also described as a conservative estimate. Taking this into account, the estimated investments for this roadmap seem to be in the right order of magnitude.

If successful, the innovation in this roadmap will lower the investments needed to deploy technologies and meet the ambitions. Several studies have estimated investments for deployment:

- For the **chemical** industry, national studies suggest EU-wide investments to be in the range of €218-238 billion.
  - Ecofys and Berenschot estimated that for the Dutch chemical industry €27 billion of investments are needed to achieve 90% GHG emissions reductions (reducing 22 MtCO<sub>2</sub> fossil fuel-related emissions) (Ecofys & Berenschot, 2018). For comparison, the total emissions of the chemical industry in Europe are 178 MtCO<sub>2</sub>; a factor of eight higher. This suggests that for the European chemicals sector, investments would be about €218 billion.
  - DECHEMA and FutureCamp estimated for the German chemical industry €68 billion of investments are needed to achieve GHG neutrality by 2050 (reducing 51 MtCO<sub>2</sub> fossil fuel-related emissions) (DECHEMA & FutureCamp, 2019). For comparison, the total emissions of the chemical industry in Europe are 178 MtCO<sub>2</sub>; a factor of 3.5 higher. This suggests that for the European chemicals sector, investments would be about €238 billion.
- For the **ceramics** sector, Cerame-Unie estimated that implementation of electric kilns (reducing emissions by 78%) would require €90 billion of investments (Cerame-Unie, 2012).
- For the European pulp and paper industry Cepi calculated cumulative investments of €6 billion to reach the 2030 CO<sub>2</sub> emission reduction targets, and an additional 18 billion

<sup>27</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

towards the 2050 targets, of which the majority is needed for investments in ‘emerging technologies’.<sup>28</sup>

- For **Dutch industry** Navigant calculated total cumulative investments and operational cost of €9-15 billion to reduce 19.4 million tonnes CO<sub>2</sub>e in the Dutch industry (scope 1) before 2030 (Navigant, 2018). For comparison, the total European scope 1 emissions of the P4Planet sectors industry are 470 million tonnes CO<sub>2</sub> (24 times as much) and need to all be abated to arrive at 100% GHG emission reduction)<sup>29</sup>.

Although the above estimates do not match the scope of P4Planet and all estimates are scenario-specific and uncertain, these studies do show that investments for deployment (Nth of a kind) are substantial and estimated to be around €800 billion<sup>30</sup>. This €800 billion is about 24 times higher than the €33.8 billion investment estimation for developing the technologies (TRL1-9). The P4Planet sectors expect deployment investments to be in the trillions, and this rough estimate might well be an underestimation. A more accurate estimation would require more detailed analysis.

## 5.7 Benefits of P4Planet’s unique approach

P4Planet is a vehicle that effectively stimulates innovation. The key benefits of P4Planet compared to regular bilateral innovation support from government to innovators are the following:

- **Community:** P4Planet brings various companies from eight sectors together and co-developed this roadmap with its members (including industry, RTOs, NGOs et al.) 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-sectorial 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. P4Planet’s cross-sectorial 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 that innovators are continuously engaged for innovations to reach the market and impact society. The 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. In this respect, the collaboration with other initiatives, partnerships and innovation funding and financing schemes is also key, because that ensures that innovation can take place rapidly.
- **Informed decisions:** P4Planet’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. That enables a coordinated management of the innovation pipeline.
- **Knowledge dissemination:** P4Planet 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. The European Community of Practice (see A-12.a) will play a major role in this. Of P4Planet project coordinators, 60% are member of P4Planet, which means that there is also a significant dissemination of knowledge to non-members.

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<sup>28</sup> 2050 Roadmap to a low-carbon bioeconomy, The forest fibre and paper industry - investing in Europe for Industry Transformation (2018)

<sup>29</sup> 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 considered an order-of-magnitude comparison only. Furthermore, P4Planet also has the ambition of near-zero landfilling and near-zero wastewater discharge and would likely also reduce emissions embedded in the fossil feedstocks.

<sup>30</sup> For the chemical industry the deployment investment estimates arrive at around €200 billion, and for ceramics this is €90 billion. These sectors account for about 36% of fossil fuel-related CO<sub>2</sub> emissions. Assuming similar investments per tCO<sub>2</sub>, the total P4Planet deployment investment estimate would be around €800 billion.

P4Planet can only be successful under the right conditions. These success factors are described for each innovation programme in Appendix A and the key factors are:

- Deployment requires a market demand for the developed innovations. Governments can play a role in **market creation**.
- **Recycling policies** should incentivize higher-value applications for secondary materials, remove hurdles for (cross-border) recycling and have adequate rules for the use of CO<sub>2</sub> as a feedstock.
- The transformation will not succeed without **enormous quantities of cost-competitive GHG emission-free energy** as demand will surge in the process industries (as well as other sectors).
- Besides the energy itself, energy transport **infrastructure** (e.g. increased electricity grid capacity and hydrogen transportation infrastructure) should also be built in time. Additional infrastructure is required for waste collection and sorting and for CO<sub>2</sub> transportation.

## Appendix A Detailed innovation programmes

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### A-1 Renewable energy integration

#### A-1.a Integration of renewable heat and electricity

This innovation programme focuses on the 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 the site or onsite enables the reduction of transmission losses and (in some cases) the transformation from direct current to alternating current can be avoided. Other synergies may exist with renewable heat.

This programme covers all renewable energy sources, including concentrated solar power or heat (see Text box 4, PV power, wind power, hydropower, and geothermal heat. Biomass is excluded as this is covered in the innovation programme “integration of bioenergy, waste, and other new fuels.” These renewable energy sources can meet demand for high temperature heat, low temperature heat, or electricity. Numerous applications in industry exist, including the following examples:

- Combining the emerging technology for steel making through 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. Such a process requires finely ground iron ore, so a grinding installation is included onsite that 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 to 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 produced by 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. Concentrated solar heat is used to heat the raw materials up to around 900 °C and the electric furnace powered by PV is used to reach the temperature required for calcination.
- Combining renewable power with CO<sub>2</sub> upgrading to CO for steel production. The renewable electricity generation can be used to directly convert CO<sub>2</sub> into CO that can be used to reduce the iron ore.
- Combining technologies in these types of projects can involve technologies under development in other innovation programmes. For example, integration of green hydrogen (A-5.b) and oxygen in existing plants, versatile storage or buffer systems (A-1.d), and clever digital systems that enable 24/7 cost-effective operation in a flexible manner (A-1.d).
- Combining paper production with solar thermal. The thermal energy is used for drying the paper, preferably optimally combined with electricity driven heat upgrading technologies.

#### **Text box 4: Solar Heat for Industrial Processes (SHIP)**

Solar heat is one of the renewable energy technologies that can be used in process industries. According to experts, the greatest potential for solar heat is in industrial processes; however, the share of industry in solar heat demand remains low. Although the solar technologies are available commercially, key questions remain regarding integration into industrial processes at different temperatures. Integration with lower temperature processes (80 °C-150 °C) is more mature (TRL3-5) than integration with higher temperatures. Technologies that generate heat at temperatures exceeding 400 °C are especially immature. Such higher temperatures can enable solar heat's use in applications like zinc distillation.

#### **A-1.a.1 Innovation objectives**

This programme's innovation objective is to demonstrate the potential renewables integration in the process industry by various demonstration projects of different renewable energy-industrial process combinations at different scales:

- Small scale (order of magnitude 10 MW) 16 demonstrations by 2030, one-third of which are demonstrated by 2024
- Medium scale (order of magnitude 100 MW) demonstrations by 2030, one-third of which are demonstrated by 2024
- Large scale (order of magnitude 1,000 MW) 4 FOAK demonstrations by 2030

#### **A-1.a.2 Impacts**

For the assumptions and methodology underlying our impact estimations, reference Appendix E .

##### ***Greenhouse gas emissions***

The technical potential GHG impact of the integration of renewables in all P4Planet sectors in 2050 is equal to the current fossil fuel combustion-related direct emissions. This is 386 MtCO<sub>2</sub> for the process industries.<sup>31</sup>

In 2024, about one-third of the small and medium scale applications are at TRL9. Assuming the small and medium scale applications cover 25% of the total potential, and the default penetration rate of 10% between 2024 and 2030, this implies that of the total 386 MtCO<sub>2</sub> in 2030 3 MtCO<sub>2</sub> is achieved in 2030 from deployment (i.e. 25%\*33%\*10%=0.8%).

There are also TRL9 projects that are done between 2024 and 2030. At 7,500 load hours (implying storage or a combination of solar and wind) and if natural gas is displaced at 56 kgCO<sub>2</sub>/GJ, the impact per project is 0.02 MtCO<sub>2</sub> for a small scale (order of magnitude 10 MW), 0.15 MtCO<sub>2</sub> for a medium scale (order of magnitude 100 MW), and 1.51 MtCO<sub>2</sub> for a large scale (order of magnitude 1,000 MW). This means that the deployment between 2024 and 2030 (10/5/4 installations in S/M/L, respectively) will directly reduce about 7 MtCO<sub>2</sub>. Therefore, the total GHG emissions impact in 2030 is estimated at 10 MtCO<sub>2</sub>e.

##### ***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, which is why demonstration projects are important.

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

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<sup>31</sup> Note that this includes some process emissions for the chemicals sector

### A-1.a.3 Programming

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

- **16 x Small scale demo** (order of magnitude 10 MW) – this will demonstrate the possibility of integrating the process industry with dedicated renewable energy generation and includes the testing of certain technologies in industrial applications. For example, solar heat for drying in ceramics and cement. Average costs of TRL 7-8 and TRL 9 demos are estimated to be €10 million.
- **8 x Medium scale demo** (order of magnitude 100 MW) – this will demonstrate the possibility of integrating the process industry with dedicated renewable energy generation at larger volumes and integrating multiple technologies. For example, solar heat for paper production, solar heat and PV for cement or PV connected to non-ferrous metals production. Average costs of TRL 7-8 and TRL 9 demos are estimated to be €20 million.
- **4 x Large scale demo** (order of magnitude 1,000 MW) – this will demonstrate integration of renewable energy in large-scale process industries. For example, chemical or steel plants with higher level of integration of multiple technologies and more complex demand response. Average costs of TRL 7-8 demos are estimated to be €50 million, and TRL9 demonstration €200 million.
- **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. Tools will be developed to help 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 and developed in so supply and demand are matched as well as possible. The system can be optimised in an integrated way using models that simulate the process and combine it with the renewable energy production. The system’s operational optimisation is part of the energy management innovation programme.

### A-1.a.4 Investment needs

Table 4: Investment needs in € million<sup>32</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Small scale demo</b>	2020-2024			16x €10	6x €10		<b>€220</b>
	2024-2030				10x €10		<b>€100</b>
	2030-2040						
	2040-2050						
<b>Medium scale demo</b>	2020-2024			8x €20	3x €20		<b>€220</b>
	2024-2030				5x €20		<b>€100</b>
	2030-2040						
	2040-2050						
<b>Large scale demo</b>	2020-2024						
	2024-2030			4x €50	4x €200		<b>€1,000</b>
	2030-2040						
	2040-2050						
<b>Research programme</b>	2020-2024					€5	<b>€5</b>
	2024-2030						
	2030-2040						

<sup>32</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

	2040-2050						
<b>Total</b>		<b>€0</b>	<b>€0</b>	<b>€520</b>	<b>€1,120</b>	<b>€5</b>	<b>€1,645</b>

#### **A-1.a.5 Success factors**

- Cost reductions in some renewable energy technologies are needed to improve the business case
- Integration of renewable energy sources is often to be combined with adjustments in the total process system and design, e.g. some process unit operations may have to be adapted to allow the new energy sources to be efficiently used
- Infrastructure is needed to transport the resources to the site and to transport produced materials from the site (which can be remote, e.g. a Spanish desert)
- Land area availability for certain renewable technologies
- New European regulation that enables fast ramp up and deployment of renewable energy production and distribution at the European level
- Policy framework that incentivises companies to fully redesign their processes and operations

## A-1.b Integration of bioenergy, waste, and other new fuels

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. Agricultural residues can be used to generate biogas, which can be used as energy or as a resource.

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).

The direct use of biomass or waste is problematic for two 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 of biomass or waste 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 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 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. Industrial processes are often not capable of dealing with this fluctuation.

The challenges for this innovation programme can be overcome by:

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

### **SPIRE project this programme builds on**

**CIRMET** brings a furnace optimisation and 25% reduction of CO<sub>2</sub> emissions due to coke replacement of biochar plus less energy for air compressors driven by waste heat. It allows ZnO to be reused in the Zn smelter or ceramic industry. It operates at TRL5 with potential to TRL7 in 2027 demonstration given €5 million in investment.

#### **A-1.b.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<sup>3</sup> (i.e. that of coal) in 2025
- Cost-effective integration of biomass in industrial applications

#### **A-1.b.2 Impacts**

For the assumptions and methodology underlying our impact estimations reference Appendix E .

#### **Greenhouse gas emissions**

In theory, all coal can be replaced by bioenergy and waste if all barriers are overcome. This would mean that the current direct emissions related to coal combustion in all process industries would be mitigated. Taking total solid fossil fuel emissions in cement and steel as proxy for the coal emissions of all process industries amounts to around 160 MtCO<sub>2</sub>.<sup>33</sup> For waste, this can only be achieved with biogenic waste, otherwise the CO<sub>2</sub> emissions would remain fossil.

This simplified estimation does not fully account for the difference between upstream emissions, and only considers combustion emissions. However, these upstream emissions can also be avoided (e.g. by using biofuels in transport of biofuels). If the biowaste is landfilled there would

<sup>33</sup> Solid fossil fuel consumption for 2018 (around 1.7 EJ) was retrieved from the energy balances (Eurostat, 2020b). For steel the transformation inputs for coke ovens are used, and transformation inputs for blast furnaces and final consumption are excluded to avoid double counting. For cement the final consumption of non-metallic minerals is used. A conservative average emission factor of 95 tCO<sub>2</sub>/TJ is assumed based on (Juhrich, 2016).

be additional GHG reductions from anaerobic digestion. If the biomass is composted, then half of the carbon would be converted into CO<sub>2</sub>.

In 2030, three installations for the pre-processing of biomass are built according to the programming, and these installations are assumed to reduce emissions by about 5 MtCO<sub>2</sub>e.<sup>34</sup>

**Text box 5: Bioenergy controversy**

Bioenergy can cause several sustainability impacts, which sometimes is cause for concern and sparks debate. For example, there are concerns that an increased demand for bioenergy would lead to deforestation and loss of biodiversity or cause food prices to increase. Such concerns should be taken seriously, and care should be taken to avoid adverse effects. The EU limits these impacts through various regulations, including obligatory certification. We do not address these issues for this innovation programme. Instead, we assume that effective regulations will be in place that ensure that only sustainable biomass will be used.

The supply of sustainable biomass is ultimately limited. Other sectors may consume a share of the available biomass to meet their energy needs. As a result, it is unlikely that biomass will serve as a silver bullet to replace all industrial fossil fuel consumption unless the sector takes measures to sustainably increase the potential. We do not take this into account in the programme and show an unconstrained technical potential (100% of energy being supplied by bioenergy).

However, this potential will likely not fully be achieved. The existing new policies scenario from IEA 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 supply in 2040 whereas it is 10% today (IEA, 2018).

**Waste**

If waste streams are used as a fuel in industry, then it will reduce landfilling. About 15 Mt of organic waste is landfilled in Europe today, including organic fraction of mixed waste and pure organic waste streams.<sup>35</sup> If this is used by the process industries instead, landfilling will be avoided.

**Competitiveness**

Bioenergy’s or waste’s competitiveness with fossil fuels depends on the pre-treatment. The following table shows how (with our illustrative set of prices for energy carriers and at a carbon price of €25/tCO<sub>2</sub>) bioenergy is competitive at prices up to €10.8/GJ. At a carbon price of €150/tCO<sub>2</sub>, bioenergy is competitive at prices up to €17.8/GJ. These prices include the costs of biomass and the costs of pre-treatment, which are 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 25 €/tCO <sub>2</sub>	2050 technology 25 €/tCO <sub>2</sub>	Current technology 150 €/tCO <sub>2</sub>	2050 technology 150 €/tCO <sub>2</sub>
<b>Emissions</b> (tCO <sub>2</sub> /GJ heat production)	0.056	0	0.056	0

<sup>34</sup> Assuming 8,000 load hours, displacing natural gas in 1 GW installation

<sup>35</sup> Organic waste streams Paper and cardboard wastes, Wood wastes, Textile wastes and Animal and vegetal wastes (subtotal, W091+W092+W093) amount to 2.1 million tonne landfilled according to (Eurostat, 2016). For mixed wastes Eurostat does not provide a separate landfilling figure for organic waste, so using data from the World Bank a fraction of 36% is estimated (including wood, food and garden waste) (World Bank, 2018). With this, the volume of organic waste in mixed waste is estimated to be 89 million tonne. Subtracting the 43 million tonnes of composted waste, this leaves 47 million tonnes of organic waste. This is assumed to be proportionally distributed over the remaining waste treatment categories (Eurostat, 2018).

Parameter	Current technology 25 €/tCO <sub>2</sub>	2050 technology 25 €/tCO <sub>2</sub>	Current technology 150 €/tCO <sub>2</sub>	2050 technology 150 €/tCO <sub>2</sub>
<b>Energy price</b> (€/GJ)	9.4 (natural gas)	10.8 (break even bioenergy price)	9.4 (natural gas)	17.8 (break even bioenergy price)
<b>Total cost</b> (€/GJ heat)	<b>10.8</b>	<b>10.8</b>	<b>17.8</b>	<b>17.8</b>

Biomass-tolerant processes are expected to be more cost-effective and increase competitiveness further if they develop to TRL9. If pre-treatment options are found to be more cost-effective, biomass-tolerant options will not be used. This may differ for sectors or situations.

### **A-1.b.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 tolerate biomass without pre-treatment (e.g. cement kilns), and for some processes such biomass-tolerant alternative processes are available. For example, in the steel sector, the Hlsarna technology enables the use of 45% bioenergy in the form of charcoal in the steelmaking process, which allows for significant GHG emission reductions. This technology is currently at TRL6-7. Another example is the CIRMET project mentioned earlier.

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

In areas with low potential for renewable power generation, biomass may also be used in an onsite combined heat and power plant.

To develop new processes that are biomass-tolerant first, 12 parallel research tracks of €4 million each are executed, followed by four pilots of €5 million each and then two TRL7-8 demonstration projects of €25 million each and two TRL9 demonstrations of €40 million each.

#### **Biomass pre-treatment**

Pre-treatment technologies for solid biomass include mechanical processing, drying, pelletisation, steaming, pyrolysis, and torrefaction. Biogas can be upgraded to biomethane, which can be used to replace fossil methane. A purer fuel could enable purer CO<sub>2</sub> and make the capture and reuse of the carbon more cost-effective.

Blast furnaces 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; the coke (higher volumes) is more difficult to replace by bio-coal because it does not tolerate impurities in the fuel.

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 the innovation programme European Community of Practice (A-12.a).

To develop this option, three TRL7-8 demonstration projects of €25 million each are programmed where the solid bioenergy option is used at scale and integrated in the process (this can be in the order of magnitude 1 MW-10 MW, or smaller in the case of decentralised applications). Three TRL9 demonstrations (in the range of 1,000 MW) are programmed of €40 million each.

### A-1.b.4 Investment needs

Table 5: Investment needs in € million<sup>36</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Biomass-tolerant processes</b>	2020-2024	12x €4					<b>€48</b>
	2024-2030		4x €5	2x €25			<b>€70</b>
	2030-2040				2x €40		<b>€80</b>
	2040-2050						<b>€0</b>
<b>Biomass pre-treatment</b>	2020-2024			3x €25			<b>€75</b>
	2024-2030				3x €40		<b>€120</b>
	2030-2040						<b>€0</b>
	2040-2050						<b>€0</b>
<b>Total</b>		<b>€48</b>	<b>€20</b>	<b>€125</b>	<b>€200</b>	<b>€0</b>	<b>€393</b>

### A-1.b.5 Success factors

- Close collaboration with the energy sector is needed
- Availability of biomass, including sustainable logistics
- Relation to industrial symbiosis – reusing waste heat for drying in pre-treatment
- Improve permitting procedures to allow for switching to biomass (the composition of the flue gas changes and include more toxic substances)

<sup>36</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-1.c Hybrid fuel transition technologies

Where 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 renewable energy options.

Going to fully renewable-powered process industries in 2050 requires a transition, and in the first decade renewable energy supply might not be sufficient to supply industrial demand. The energy infrastructure may not exist to provide the volumes of renewable energy. 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 (in combination with flexibility and demand response).

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

### A-1.c.1 Innovation objectives

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

### A-1.c.2 Impacts

For the assumptions and methodology underlying our impact estimations reference Appendix E .

#### ***Greenhouse gas emissions***

This programme mainly effects 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 instead of in 2050.

Hybrid technologies target fossil fuels that are used for heating and reduction processes. This amounts to around 386 MtCO<sub>2e</sub> of GHG emissions in the process industry. Of these emissions, two-thirds are replaced by renewable energy.<sup>37</sup> This implies a total reduction of 257 MtCO<sub>2e</sub>. A different approach is used to estimate this impact and it cannot be compared to other impact figures in this roadmap.

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 of power or carbon prices on competitiveness. The CAPEX of hybrid boilers is assumed to be similar to conventional gas-fired boilers. The following table shows that, with our illustrative price for natural gas, electricity should be available at an electricity price below €10.8/GJ to be competitive at a carbon price of €25/tCO<sub>2</sub> and below €17.8/GJ at a carbon price of €150/tCO<sub>2</sub>. Electricity is only used during times when prices are competitive (assumed two-thirds of the time in this example). As only the cheapest electricity is used, the average electricity price can be higher.

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<sup>37</sup> Note that this includes some process emissions in the chemicals sector

Parameter	Current technology 25 €/tCO <sub>2</sub>	2050 technology 25 €/tCO <sub>2</sub>	Current technology 150 €/tCO <sub>2</sub>	2050 technology 150 €/tCO <sub>2</sub>
CAPEX (€/GJ heat production/ year)	0.5	0.5	0.5	0.5
Capital recovery factor	11% (i=10%; L=25yr)	11% (i=10%; L=25yr)	11% (i=10%; L=25yr)	11% (i=10%; L=25yr)
Emissions (tCO <sub>2</sub> /GJ heat production)	0.056	0.056 * 1/3	0.056	0.056 * 1/3
Energy consumption (GJ)	1	1	1	1
Energy price (€/GJ)	9.4 (natural gas)	1/3 * 9.4 (natural gas) 2/3 * 10.8 (break even electricity price)	9.4 (natural gas)	1/3 * 9.4 (natural gas) 2/3 * 17.8 (break even electricity price)
<b>Total cost (€/GJ heat)</b>	<b>10.9</b>	<b>10.9</b>	<b>17.9</b>	<b>17.9</b>

There is value in reliable energy availability. Because there are two options, production is not affected if one option's supply is disrupted. This results in a reduction of fossil fuel imports and increases energy security for Europe.

### A-1.c.3 Programming

- **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. Key parameters should be explored (e.g. flame properties, fume volume, interaction with the process). Two demonstration programmes are planned: one for a high pressure system and one for a low pressure system. The demonstration projects will be done in three sectors each, will finish before 2025, and will require €5 million each. Another six TRL9 demonstration projects are programmed, three of which will be complete before 2024. The investments for these projects are estimated at €10 million.
- **Integration of hybrid technologies** – Some technologies are still under development. For example, hybrid ceramic kilns require the demonstration of electric kilns first (see A-3.b). 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 €10 million each, followed by two first-of-a-kind installations of €40 million each.

### A-1.c.4 Investment needs

Table 6: Investment needs in € million<sup>38</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Upscaling of hybrid technologies</b>	2020-2024			6x €5	3x €10		€60
	2024-2030				3x €10		€30
	2030-2040						€0
	2040-2050						€0
<b>Integration of hybrid technologies</b>	2020-2024			2x €10			€20
	2024-2030				2x €40		€80
	2030-2040						€0
	2040-2050						€0
<b>Total</b>		€0	€0	€50	€140	€0	€190

<sup>38</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

#### **A-1.c.5 Success factors**

- Low-cost renewable energy needs to be available for sufficient hours per year to enable a business case
- Infrastructure that can transmit renewable energy is key. If insufficient grid capacity is available to supply the energy needs of the installation, it is unlikely to be economical.

## A-1.d 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. This sector coupling enables synergies in the overall energy system.

Process industries have the option of consuming less energy when less energy is available (and prices are high) or of consuming more energy when a surplus of energy is available (and prices are low or even negative). Less energy can be consumed if it is produced slowly or less, or by taking energy from storage. More energy can be consumed if more is produced (producing faster or producing more intermediates if there is excess production capacity and storing them), or by putting energy in storage (see the following box for an example from the aluminium sector).

### Text box 6: Virtual Battery example

TRIMET Aluminium allows one of its pot-rooms in its Essen plant to operate as an energy storage or virtual battery. Its output can vary by about 25%, based on a nominal load of 90 MW, providing a virtual storage capacity of approximately 2,100 MWh. This is comparable to a medium sized pumped-storage power plant.

To ensure flexible control of its electrolysis cells, TRIMET Aluminium developed a process technology that maintains a constant energy balance within the cell, even with a fluctuating energy supply. A major challenge is to sustain continuous and efficient production under these conditions, avoiding any interruptions in the smelting process and ensuring that delivery obligations are met. As part of this process, each aluminium electrolysis cell contains 10 tonnes of liquid aluminium. Depending on the increase or decrease in production, the level of liquid can be adjusted to ensure that production fluctuations do not interfere with the continuous processing.

Fully implemented, the three TRIMET smelters in Germany (located in North Rhine-Westphalia and Hamburg) could increase the country's pumped storage capacity - currently 40 GWh - by nearly 40%. The family-run business is investing around €36 million into this showcase demonstration plant.

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

### SPIRE project this programme builds on

**SUSPIRE** develops energy recovery systems from residual heat streams by using new Heat Transfer Fluids (HTF) and Phase Change Materials (PCM) especially for energy capture and storage linked to heat exchangers. This development is at TRL6-8, with a prototype currently running and already 16% GHG-emission reduction. It can be clustered with I-THERM.

#### A-1.d.1 Innovation objectives

- Substantial increase in flexibility of the process industries
- Increase response rate of flexibility
- Development of efficient and effective energy / heat storage technologies

### A-1.d.2 Impacts

For the assumptions and methodology underlying our impact estimations reference Appendix E .

#### **Greenhouse gas emissions**

In process industries, flexibility and demand response enables the industries to use 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 P4Planet sector fossil fuel combustion emissions (between 4 MtCO<sub>2</sub> and 39 MtCO<sub>2</sub>). We take the average of the range, which is 21 MtCO<sub>2</sub>.

Three out of 12 TRL9 projects in this programme are completed by 2024, so assuming that this 25% of TRL9 projects represents 25% of the technical potential, and assuming that 10% of this technical potential is achieved through deployment until 2030, then the reduction in 2030 is 0.5 MtCO<sub>2</sub> (2.5% of 21 MtCO<sub>2</sub>). Additionally, six TRL9 projects are completed by 2030, which combined can have an estimated impact of around 0.05 MtCO<sub>2</sub>.<sup>39</sup> This results in a total of 0.6 MtCO<sub>2</sub> in 2030.

#### **Competitiveness**

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

The stabilising effect on the grid enables higher renewables penetration and reduces energy system costs as the grid requires less capacity.

### A-1.d.3 Programming

- **Explore potential flexibility in existing processes** – This can include running processes at somewhat higher temperatures, which leads to faster production or clustering electric arc furnaces to achieve switchable capacities of batch processes in the steel sector. 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 Digital plant operation in A-13.c). Eight demonstration projects are foreseen in different regions and sectors, which enables analysis of the potential in different circumstances. The expected investment need is €2 million per demo on average. TRL9 demonstration is programmed where digital tools for process control and integrated planning and scheduling are integrated in industrial plants (see Autonomous integrated supply chain management in A-13.e). This is estimated to cost around €20 million per project. Six projects are programmed (three before 2024, three after 2024 and before 2030), one FOAK per sector.
- **Redesign processes to enable more flexibility** – When companies have already mapped the opportunities for flexibility, the next step is to change the process to allow for more flexibility. If a bottleneck limits flexibility in the process that, its removal can deliver more flexibility and associated revenues. On the other hand, temporary storage of heat during moments of process failure will further improve energy efficiency and flexibility. This should be confirmed in four demonstration projects of €5 million each. The FOAK demonstration (TRL9) is combined with the six projects mentioned above.
- **Add flexibility by means of storage** – In some cases, onsite 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

<sup>39</sup> Assuming 6.1 GW size installations using natural gas with 5% energy savings

used later in batch processes to bridge the time between batches. This storage can be in the form of electricity, heat, or other energy vectors (excluding hydrogen, this is included under the innovation programme Hydrogen storage in A-5.c). For heat storage, there is a specific focus on technologies that allow heat storage for over a week. The projects will aim at integrating existing technologies in the process industries. As many technological options exist, eight demonstration projects are programmed at €2 million each (typically relatively inexpensive at pilot scale). Then, the large-scale integration of storage is programmed (combined again with digital tools) in three FOAK installations of €20 million each.

- **New processes with faster response rate** – The flexibility potential can be stretched by exploring new processes that are able to quickly ramp up and then down again. Such new technologies would not run at full capacity, but only during times when electricity is cheap. Therefore, the process efficiency is less important than for processes that run continuously. Existing low TRL processes will be developed and piloted. Six pilots are foreseen and, depending on the results (and the market for flexibility), can be demonstrated. An evaluation should take place in 2024. The six pilots are estimated to require investment of €10 million each. The subsequent three demonstrations are expected to cost €25 million each, and if successful the FOAK full-scale demonstration of the technology is estimated to require €50 million of investments.

#### A-1.d.4 Investment needs

Table 7: Investment needs in € million<sup>40</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Explore potential flexibility in existing processes</b>	2020-2024			8x €2	3x €20		€76
	2024-2030				3x €20		€60
	2030-2040						€0
	2040-2050						€0
<b>Redesign processes to enable more flexibility</b>	2020-2024			4x €5			€20
	2024-2030						€0
	2030-2040						€0
	2040-2050						€0
<b>Add flexibility by means of storage</b>	2020-2024			8x €2			€16
	2024-2030				3x €20		€60
	2030-2040						€0
	2040-2050						€0
<b>New processes with faster response rate</b>	2020-2024		6x €10				€60
	2024-2030			3x €25			€75
	2030-2040				3x €50		€150
	2040-2050						€0
<b>Total</b>		€0	€60	€127	€330	€0	€517

#### A-1.d.5 Success factors

- Infrastructure should be available for heat and electricity 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 onsite storage
- Transmission system operators (TSOs) must be willing to pay for flexibility. TSOs can avoid increasing grid capacity because of increased flexibility at the demand side. This can differ by location.

<sup>40</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-2 Heat reuse

### A-2.a Advanced heat reuse

Process industries use many thermal processes, and there is often much residual heat. In many cases this residual heat is reused onsite (for example, to pre-heat raw materials, thereby reducing energy needs). In some cases, (a share of) the residual heat is reused outside of the boundaries of the company, either in industrial applications or in the built environment. However, there a large potential for heat reuse remains untapped.

In practice there are various barriers that inhibit the use of the residual heat:

- **State** – If the residual heat is in a solid material, it is difficult to transfer the heat to a fluid to be able to transport it to the application.
- **Distance** – If the application for the heat is too far away, the transportation of the heat is too expensive and the leakage of heat during transport makes the business case unattractive.
- **Temperature** – Where residual heat is available, the temperature is often too low for locally available applications. Some heat exchangers (materials) are not tolerant to low temperatures because of condensation and corrosion. Heat can be upgraded (for example, using heat pumps) but this also makes the heat more costly.
- **Contaminants** – The quality of the heat medium can be insufficient (presence of air and/or contaminants), and the technologies to clean/separate the media can be too expensive for the heat application.
- **Lock-in** – The industrial process is optimised over the years and including a heat recovery device is difficult as it impacts the parameters of the process.

The innovation to overcome non-technological barriers is covered in innovation programmes Development of Hubs for Circularity (A-12.b) and European Community of Practice (A-12.a).

#### **SPIRE project this programme builds on**

**ETEKINA** demonstrates cost-effective waste heat recovery in industrial applications for non-ferrous, steel, and ceramics industry at a TRL7 with strong reductions per sector at the level of GHG emission reduction and waste generation. Deployment at TRL9 in 2024 will deliver 0.4 MtCO<sub>2</sub> GHG reductions and 200 GWh/yr reduction in energy use per installation. Installation in one non-ferrous, steel, and ceramic facility will save €17.5, €90, and €155 thousand, respectively.

#### **A-2.a.1 Innovation objectives**

It is often possible to reuse the waste heat, but the alternative (typically fossil fuel combustion to generate new heat) is more economically attractive. Therefore, the goal of this innovation programme is to develop technological innovations that enhance the business case for heat reuse by increasing the applicability of heat exchangers so more heat can be recovered.

Recovered heat can be used to heat other process flows, in heat pumps (see innovation programme Heat pumps in A-3.a), in the built environment (see innovation programme Development of Hubs for Circularity in A-12.b), or converted to electricity (not programmed here).

#### **A-2.a.2 Impacts**

For the assumptions and methodology underlying our impact estimations reference Appendix E .

#### **Greenhouse gas emissions**

Heat is mainly fossil but over time will become renewable. This transition can be smoothed (lower use of scarce renewable energy and increased efficiency [competitiveness]) by increased reuse of heat. Overall, a high level estimate using expert judgement of the achievable efficiency gains/GHG emission reduction would be an order of magnitude of 10% in 2050 (small in 2030).

### A-2.a.3 Programming

The programming of this innovation programme focuses on improved heat exchangers, which makes it economically feasible to exchange more heat at the same costs (smarter design with, for example, a bigger surface without fouling), or by allowing heat exchange in areas where it currently is not feasible to do so (for example: plastic heat exchangers, which can be applied in areas where steel heat exchangers would corrode by condensation of acids, thus to recover low temperature residual heat). The application of such heat exchangers needs to be proven in an increasing number of industrial sectors. Digitalisation of maintenance (remote monitoring, online detection of corrosion and fouling) improves the efficiency of heat exchangers during operation.

### A-2.a.4 Investment needs

Innovation pipeline is derived from eight TRL9 projects of €5 million each, and the required development to bring new technologies to TRL9.<sup>41</sup>

Table 8: Investment needs in € million<sup>42</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Advanced heat reuse	2020-2024	12x €1	6x €2	2x €3	1x €5		€35
	2024-2030		4x €2	3x €3	2x €5		€27
	2030-2040			2x €3	3x €5 2x €5		€31
	2040-2050						€0
<b>Total</b>		<b>€12</b>	<b>€20</b>	<b>€21</b>	<b>€40</b>	<b>€0</b>	<b>€93</b>

### A-2.a.5 Success factors

- Digital technologies to develop the next generation of heat exchangers (e.g. using artificial intelligence to develop new designs); this is included in innovation programme Digital process development and engineering in A-13.b.
- Heat storage can increase the applicability of residual heat (for example, in case of batch processes); development of heat storage systems is included under innovation programme Flexibility and demand response (A-1.d).
- Integration of the next generation of heat exchangers will often require adjustments in the process unit operations and the overall process design and heat system. These are included under innovation programme: Breakthrough efficiency improvement (A-9.b)

<sup>41</sup> The order of magnitude of these investment estimates are highly uncertain

<sup>42</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-3 Electrification of thermal processes

### A-3.a Heat pumps

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 that can deliver heat up to 100 °C. Research is devoted to increasing the temperature of the delivered heat. Some systems are capable of delivering temperatures of 150 °C. However, no commercial systems are available for medium or intermediate temperature heat pumps. The 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). However, these developments are in general at low TRL (laboratory research, functional models, proof of concept: TRL3-4).

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

The complexity and cost of integration is an issue when integrating heat pumps into existing processes. Effective use of these techniques inherently requires vapor without contaminants and with low air content. Though many industrial drying technologies are highly efficient in energy transfer for water evaporation, most processes result in a vapor with contaminants or too high air content so that latent heat cannot efficiently be recovered with heat pump and vapour recompression technologies. The challenge is to innovate in the drying technologies in order to solve these issues. These process innovations are included under [innovation programme: Breakthrough efficiency improvement \(A-9.b\)](#)

Especially if additional infrastructure needs to be built, the business case becomes challenging. The process-integration of heat pumps is an effective manner of integration, meaning the heat pump is not part of the general utilities, but is integrated in a specific process that uses waste heat from the process to provide heat. An example is the use of a heat pump in combination with a distillation column that uses heat from the condenser to feed the reboiler.

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

#### **SPIRE project this programme builds on**

**DRYFiCIENCY** demonstrates open and closed loop, industrial heat pumps (up to 160 °C) for the recovery of waste heat with savings up to 80% and 50% on GHG emissions. It is developed at TRL7.

#### **A-3.a.1 Innovation objectives**

The innovation challenges differ by 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 developed and there are various technical challenges that need to be solved. Technologies with the potential to reach temperatures up to 250 °C are 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 for even higher temperatures, but these technologies are at a lower TRL.

Temperatures above 500 °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 include the following:

**Reduce CAPEX of heat pumps up to 150 °C to 200 €/W<sub>th</sub> in 2025 and (market driven) 150 €/W<sub>th</sub> in 2050**

– Because of their high efficiency, heat pumps can compete with fossil fuels on fuel costs 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 3 times as high as the cost of the fossil fuel. However, the high upfront investment cost of current heat pumps leads to unattractive payback times. The large-scale deployment of heat pumps requires a reduction of the CAPEX. The 2030 target will trigger the first wave of heat pump deployment; afterwards, the standardisation and supply chain optimisation will decrease costs to meet the 2050 target.

- **Developing heat pumps and MVR up to 250 °C to TRL9 in 2030** – Innovation is necessary to extend the temperature operating range of compression heat pumps:
  - Refrigerants must be available with good thermophysical properties and low global warming potential (e.g. HFOs)
  - Lubricants must ensure the correct operation of the lubricant-refrigerant mixture within the operating temperatures, compressor technology, and suitable vapour compression cycle
  - Components must be able to withstand high temperatures, and novel concepts and cycles.
- **Developing heat pumps and MVR higher than 250 °C to TRL9 in 2040** – It may be possible to push heat pumps to even higher temperatures. This will be researched, and at a later stage it will be determined whether it 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 fossil-fuelled systems, the heat temperature does not impact the efficiency of heat production. For heat pumps, the efficiency depends on waste heat temperature levels and the 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. Engineering firms are not well-informed enough about the potential and possibilities for heat pumps integration because the market is not asking for it. Therefore, projects aimed at knowledge transfer to the engineering sector and technology providers and demonstration projects are required. Heat pump integration should be coordinated with innovation programs such as Digital process development and engineering (for advanced process modelling), Heat reuse (for innovative heat exchangers), Breakthrough efficiency improvement and Circular regions (for the optimisation over multiple plants).
- **Knowledge and awareness about heat pumps** – A major barrier to heat pump implementation is the lack of knowledge about integrating medium and high temperature heat pumps in industrial processes. There is also a low level of awareness of the technical possibilities and the economically feasible application potential among users,

consultants, investors, plant designers, producers and installers. Knowledge sharing and creating awareness are key to the success of this programme.

### A-3.a.2 Impacts

For the assumptions and methodology underlying our impact estimations reference Appendix E .

In most P4Planet sectors a substantial part of the CO<sub>2</sub> 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<sub>2</sub> emissions to near zero.

#### Greenhouse gas emissions

Sector	Current Heat-related Emissions in EU, MtCO <sub>2</sub> e	Emissions targeted (2030) by IP, %	Emissions targeted (2050) by IP, %	Emission reduction impact 2030, MtCO <sub>2</sub>	Emission reduction impact 2050, MtCO <sub>2</sub>
Cement	41	N/A	N/A	0	0
Steel	48 <sup>43</sup>	0%	0% <sup>44</sup>	0	0
Chemicals	124	±0.8% <sup>45</sup>	±10% <sup>46</sup>	1	12.4
Ceramics	16	0% <sup>47</sup>	5% <sup>48</sup>	0	0.8
Non-ferrous metals	10	0% <sup>49</sup>	±15% <sup>50</sup>	0	1.4
Minerals	6	N/A	N/A	0	0
Water	0	N/A	N/A	0	0
<b>Total P4Planet</b>	<b>244</b>			<b>1</b>	<b>14.6</b>

In addition to the sectors in the table above, there can be impacts to the pulp and paper and food industry when reduced costs of heat pumps until 150 °C triggers uptake of these heat pumps in these sectors.

The impact could be higher when switching to direct electric heat methods (see innovation programme Electricity-based heating technologies in A-3.b), as this reduces the availability of waste heat that has high enough temperatures to preheat process flows. Preheating using heat pumps becomes attractive.

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

#### Competitiveness

<sup>43</sup> In the steel sector fossil fuels are not only used for generating heat, but also as a reductant. If the fossil reductant is used it cannot be substituted by electricity. This means that blast furnace emissions and the emissions from power generation using blast furnace gas are not targeted by electric heating. According to (IEA GHG, 2000) this is together around 75% of emissions (70% blast furnace emissions and 5% power generation emissions).

<sup>44</sup> Currently enough heat (and fuel gas) is available from high temperature processes; this potential could change when switching to DRI or electrochemical processes.

<sup>45</sup> Estimates based on 10% of the share of the heat use below 150 °C (Fleiter, 2017) divided by 2 to take into account that application of heat pumps will not always be possible, without taking the emissions associated with the current production of hydrogen, ammonia and methanol (estimated to be around 30% of the chemical industry's current emissions, based on (Ecofys, 2009)) into account; part of these emissions, which are dependent on the fuel used, are typically considered process emissions.

<sup>46</sup> Estimates based the share of the heat use below 500 °C (Fleiter, 2017) divided by 2 to take into account that application of heat pumps will not always be possible, without taking the emissions associated with the current production of hydrogen, ammonia and methanol (estimated to be around 30% of the chemical industry's current emissions, based on (Ecofys, 2009)) into account; part of these emissions, which are dependent on the fuel used, are typically considered process emissions..

<sup>47</sup> Heat use < 150 °C very limited for ceramics; heat required for drying processes is typically around 180-200 °C.

<sup>48</sup> Expert opinion: 10% of the heat demand for ceramics is below 500 °C (pre-heating and drying); this has been divided by 2.

<sup>49</sup> Heat use <150 °C very limited for nonferrous metals.

<sup>50</sup> Rolling and extruding aluminium or copper and some secondary processes require temperatures below 500 °C.

Heat pumps will primarily displace gas boilers. The following calculation shows that, compared to a typical gas boiler, the 2050 heat pump would be competitive even at an electricity price of €40/GJ under a €25/tCO<sub>2</sub> carbon price. That is substantially higher than the projected industrial electricity price in 2050 (around €16/GJ); see E-6. The application of heat pumps can often be competitive, although much depends on the local situation (like distances). Under a €150/tCO<sub>2</sub> carbon price the heat pump is competitive at electricity price of €63 per GJ.

Parameter	Gas boiler at €25/tCO <sub>2</sub>	Heat pump at €25/tCO <sub>2</sub>	Gas boiler at €150/tCO <sub>2</sub>	Heat pump at €150/tCO <sub>2</sub>
<b>CAPEX</b> (€/GJ heat production/year)	0.03	0.3	0.03	0.3
<b>Capital recovery factor</b>	11% (i=10%; L=25yr)	11%	11%	11%
<b>Emissions</b> (tCO <sub>2</sub> /GJ heat production)	0.056	0	0.056	0
<b>Carbon price</b> (€/tCO <sub>2</sub> )	25	25	150	150
<b>Energy consumption</b> (GJ energy input/GJ heat output)	1.1	0.3	1.1	0.3
<b>Energy price</b> (€/GJ)	9.4 (natural gas)	40 (electricity)	9.4	63
<b>Total cost</b> <sup>51</sup> (€/GJ heat)	<b>12</b>	<b>12</b>	<b>19</b>	<b>19</b>

### A-3.a.3 Programming

Cost reduction requires the development of the supply chain (i.e. development of components such as compressors and working fluid). Potential suppliers must also (further) standardise solutions. Studies show that standardisation for 2-5 MW<sub>th</sub> offers the greatest potential for widescale implementation. To achieve the cost target for the development of (cost) optimised solutions and demonstration projects, a broad range of applications are necessary. Cooperation with non-P4Planet 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 are programmed.

Vapour recompression is a technology that offers great potential for 2030. While components are 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 new (axial, centrifugal) compressor technology is expected to enable 180 °C.

Use of heat pumps for higher temperatures (>250 °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 in development:

#### 1. Demonstrate heat pumps up to 150 °C:

- **FOAK demonstration of non-integrated heat pump below 150 °C** – first retrofitting at least two large heat pumps (2021) to address multiple applications. This will generate more knowledge of the technology. Supply chain participants must be involved (compressor manufacturer, heat pump supplier, multiple end users), as well as engineers. Two projects \* €20 million = €40 million.
- **FOAK demonstration of process integrated heat pump below 150 °C** – integrating solutions in processes for various applications (like distillation units, or dryer systems, sold as a package and redesigning the process equipment, for example, the sizing of the heat exchangers). Demonstrate the benefit of process

<sup>51</sup> Only energy costs and CAPEX for heat generating equipment are considered, others are excluded.

integration, together with digitalisation to develop tools (advanced process modelling). Five projects \* €8 million = €40 million (2025).

**2. Coordinated support action on market potential and business models:**

- Conduct a market study that includes dissemination activities while also addressing potential and barriers involving engineering firms and all other relevant actors. Support national implementation programmes to help with differences in regulations and market organisations. Update this study later depending on situation in 2024. €1 million per study \* two studies = €2 million.
- Investigate and develop new business models, potentially with other sectors (energy, financial services). Including workshops, ideation, conferences. €1 million.

**3. Develop heat pumps up to 250 °C:**

Develop heat pumps based on the conventional systems with gas-liquid conversions and with new media. Different closed-cycle compression heat pumps are applicable for this temperature range, with key differences including the types of refrigerant and the type of compressor. To ensure optimal efficiency, the heat pump design should match the characteristics of the heat source and sink (continuous temperature, for example, in case of evaporation; or varying temperature [glide] in case of heating).

- **Research action heat pumps until 250 °C** - From TRL3-4 to 5 in 2021-2025 – conduct R&D for four technologies \* €5 million = €20 million
- **Further development of heat pumps until 250 °C** – from TRL5-7 for selected technology. One project of €10 million (2026-2030).
- **FOAK demonstration heat pumps until 250 °C** - from TRL7 to three TRL9 projects in 2035, totalling €20 million. This also assumes that supply chain partners are supported additionally.

**4. Develop heat pumps above 250 °C.** There are two possibilities for developing heat pumps that deliver heat at a temperature above 250 °C. Using high temperature refrigerants in compression heat pumps, or developing new concepts with new systems (for example, gas turbine, Stirling motor, thermo-acoustical) and with different efficiencies:

- **Research action heat pumps above 250 °C** – to TRL4-5 in 2030 to decide whether these heat pumps can become competitive. If so, additional development towards TRL9 in 2040. This is rapidly possible due to lessons learned from lower temperatures. R&D for six technologies \* €5 million = €30 million. If successful, a pilot and demo could occur between 2030-2040.
- **Further developing heat pumps above 250 °C** – to TRL7-8 for selected technology. Three projects of €10 million (2030-2035).
- **First of a Kind demonstration heat pumps above 250 °C** - to TRL9 in 2040 – three FOAK demonstrations of €20 million each. This also assumes that supply chain partners are supported additionally.

**A-3.a.4 Investment needs**

Table 9: Investment needs in € million<sup>52</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Demonstrate heat pumps up to 150 °C</b>	2020-2024				2x €20		<b>€40</b>
	2024-2030				5x €8		<b>€40</b>
	2030-2040						<b>€0</b>
	2040-2050						<b>€0</b>
	2020-2024					2* €1+ €1	<b>€3</b>

<sup>52</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Coordinated support action on market potential and business models</b>							
	2024-2030						€0
	2030-2040						€0
	2040-2050						€0
<b>Develop heat pumps up to 250 °C</b>	2020-2024		6* €5				€30
	2024-2030			3*€10			€30
	2030-2040				3*€20		€60
	2040-2050						€0
<b>Develop heat pumps above 250 °C</b>	2020-2024		6* €5				€30
	2024-2030			3*€10			€30
	2030-2040				3*€20		€60
	2040-2050						€0
<b>Total</b>		<b>€0</b>	<b>€60</b>	<b>€60</b>	<b>€200</b>	<b>€3</b>	<b>€323</b>

### A-3.a.5 Success factors

- **Sufficient affordable renewable electricity.** The introduction of large amounts of renewable electricity systems requires the availability of a suitable electricity infrastructure as well as changes to the regulation and organisation of the electricity grid and markets. This offers opportunities for novel stakeholders and business models.
- **Supportive policy framework.** Financing instruments are needed to support the implementation in the transition phase when CAPEX is 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 SMEs, 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.
- **Cost-effective integration of heat pumps in processes** Integration of the next generation of heat pumps will often require adjustments in the process unit operations and the overall process design and heat system. These are included under innovation programme: Breakthrough efficiency improvement (A-9.b)

## A-3.b Electricity-based heating technologies

This innovation programme addresses electric technologies other than heat pumps that can provide heat. Heat pumps may not be used because the required temperature level or absence of waste heat does not allow their use, or because the integration of the other heating technology offers benefits.

### A-3.b.1 Innovation objectives

A wide range of technologies, such as microwave heating, infrared, and inductive heating, is used within other sectors (such as pulp and paper and food). In these sector further emission reduction can still be achieved with more smartly using the specific ability of high frequency technologies for local heating, thus for profile corrections avoiding overheating of other parts of the product. However, these technologies find limited application within the other P4Planet sectors where energy cost is a more important part of the product cost. Other technologies (such as plasma technology) are still at low TRL for application in the P4Planet sectors. A high degree of industry electrification implies these technologies need to be fully utilised in the P4Planet sectors.

This innovation programme also focuses on electrical furnaces delivering temperatures of 800 °C or higher. Such furnaces include cement kilns, steam methane reformers, ceramic furnaces, steam cracking furnaces, continuous furnaces for steel slabs, and steel-based long products.

In some of these cases, transforming the process from fossil-fuelled to electrically driven will translate into a one-on-one replacement of the energy source without major changes to the process side. Thus, the heating technology can be considered a retrofit in an existing process. The business case relies strongly on the cost of electricity versus the cost of fossil fuels and CO<sub>2</sub> pricing.

However, replacing the fossil heat source by an electrical heat source creates new options for process design. This brings the possibility for more competitive processes, for example because the integration of electrical heating is more efficient than the fossil-fuelled alternative. The roadmap for the Australian industry (Beyond Zero Emissions, 2018) provides examples of a number of such applications: inductive melting (steel, non-ferrous), drying processes in the chemical industry, and drying in the ceramics industry. However, it also means the development of novel processes.

Therefore, for the programme, a distinction is made between processes that:

- Heat only 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 delivers efficiency gains in the process but requires a process redesign.

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

Efficiency gains	Based on existing process:	Requiring process redesign:
<b>No efficiency gains in the process side</b>	2030-2040: <ul style="list-style-type: none"> <li>• Ceramics furnace</li> <li>• Reforming</li> </ul>	2021-2040: <ul style="list-style-type: none"> <li>• Electric cracking</li> <li>• Lime furnace</li> <li>• Cement furnace</li> </ul>
<b>Efficiency gains in the process side</b>		2021-2035: <ul style="list-style-type: none"> <li>• Ceramics (drying techniques, e.g. MW)</li> <li>• Inductive melting</li> <li>• Inductive heating, e.g. of steel products</li> <li>• Electric cracking (better temperature control better selectivity to High Value Chemicals)</li> </ul>



This innovation programme will to demonstrate (TRL9) electrical heating at high temperatures and using advanced heating technologies before 2040 for all applications, more specifically:

- For 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.<sup>53</sup>

Electric boilers are described in innovation programme Hybrid fuel transition technologies in A-1.c.

### A-3.b.2 Impacts

For the assumptions and methodology underlying our impact estimations reference Appendix E .

In most P4Planet sectors a substantial part of the CO<sub>2</sub> 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<sub>2</sub> emissions to near zero.

#### Greenhouse gas emissions

Sector	Current Heat-related Emissions in EU, MtCO <sub>2</sub>	Emissions addressed by the IP 2030, %	Emissions addressed by the IP 2050, %	Emission reduction impact 2030, MtCO <sub>2</sub>	Emission reduction impact 2050, MtCO <sub>2</sub>
Cement	41	0%	±100%	0	40.8
Steel	48 <sup>54</sup>	0%	±5% (steel glowing and rolling)	0	2.4
Chemicals	124	±0.4% <sup>55</sup>	±25% <sup>56</sup>	0.5	31
Ceramics	16	±0.1% <sup>57</sup>	100%	0	16
Non-ferrous metals	10	0%	100%	0	10
Minerals	6	0%	Lime sector: ±100%	0	6
Water	0	0%	Close to 100%	0	0
<b>Total P4Planet</b>	<b>244</b>			<b>0.5</b>	<b>106</b>

#### Waste

No waste formation is prevented. However, in some sectors, waste flows are currently used as fuel, which would be replaced by using electrical furnaces and lead to a need to process that waste:

- **Cement** – Uses a variety of waste (solid and liquid) to fuel kilns. This would need to be processed using the variety of recycling options discussed in the rest of this report.
- **Lime** – Uses solid waste and spent solvent to fuel kilns. This would need to be processed using the variety of recycling options discussed in the rest of this report.

<sup>53</sup> The assumption here is that the CAPEX is less critical for these technologies, as they also deliver efficiency gains.

<sup>54</sup> In the steel sector fossil fuels are not only used for generating heat, but also as a reductant. If the fossil reductant is used it cannot be substituted by electricity. This means that blast furnace emissions and the emissions from power generation using blast furnace gas are not targeted by electric heating. According to (IEA GHG, 2000) this is together around 75% of emissions (70% blast furnace emissions and 5% power generation emissions).

<sup>55</sup> Assuming around 50 crackers in Europe, of which one would be electrified in 2030.

<sup>56</sup> This relates to the potential of electric cracking; the estimate is based on the share of GHG emissions coming from the production of High Value Chemicals, relative to the overall sector's GHG emissions excluding nitric acid – which has largely be abated – using data > 10 years old (Ecofys, 2009). Upward potential could come from electrifying the heat generation of the current SMR process (around 20% of emissions) and from other applications in the chemical industry.

<sup>57</sup> Based on the assumption that there are order of magnitude 1000 ceramics installations in Europe.

- **Chemicals** – In crackers, the outlet for combustible waste gases (the furnaces) is no longer available. Hydrogen and methane could be used as feedstock or raw material of downstream plants or as fuel for energy generation (if still applicable). This is addressed in innovation programme Electrically driven separation in A-4.b.

### **Competitiveness**

Capital costs are unknown.

For the applications where the impact is just a different way to provide energy: There are relevant differences between the efficiencies of furnaces/kilns in 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 only 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 because of faster processing time or start-up, improved yields or quality, or improved control. These impacts are specific for the combination of heating technology and application.

### **A-3.b.3 Programming**

The innovation programme focuses on integral development of the process and the heating technology to come to an optimal solution:

- **Fundamental knowledge** of the process (MIT, 2019) (“how the brick dries”) is necessary to understand how to optimise processes (drying, sintering, melting), the advanced heating technologies, and models and methods.
- **Integration of electric** heat solutions in the process development is key to cost-effectiveness; this will require (re)designing the process to maximise the benefits of new heating technology. Cooperation with equipment suppliers and engineering companies is also necessary.

For several applications, the development focuses on the electrical delivery of the heat to the kiln, furnace, or reactor. This applies to ceramics, lime and cement (technology currently at TRL2-3), and reforming (technology currently at TRL3-4).

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

- For a cracker (technology currently at TRL2-3), the heating mechanism and intensity and the speed of cooling are 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 also a range of technologies: resistance heating, inductive heating, microwave heating, ultrasonic plasma heating, radio frequency heating and infrared heating. Catalysts and reactors might need to be changed too.

This means:

- **Electric cracking** and **electric kilns for cement, lime, and ceramics** will be developed in four stages, delivering TRL9 in 2030 (for the crackers and for ceramics) and in 2035 (for cement and lime), with **research programmes for enabling topics** laying the foundation.
- Development of **highly flexible electrical heated reactors** at delivering load-flexible reactors at TRL9 in 2036.
- A programme focussing on **highly efficient electrical heating** for ceramics aims at delivering a more energy efficiency ceramics kiln at TRL9 in 2035.

Electrical heating could offer innovative potential in other sectors as well.

### SPIRE project this programme builds on

**SIMPLIFY** aims to modify batch production in the chemical industry to continuous processes with applying electricity in the form of microwaves and ultrasound. The project aims to reach TRL6 while a subsequent project will reach TRL9 by 2026. A 60% reduction in GHG emissions and a 30%-70% reduction in waste is expected, while increasing competitiveness by 20%-45%.

#### A-3.b.4 Investment needs

Table 10: Investment needs in € million<sup>58</sup>

Technology:	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total:
<b>Research on enabling technologies</b>	2020-2024	€20					€20
	2024-2030		10x €4				€40
	2030-2040						€0
	2040-2050						€0
<b>Electric heating in ceramics/cement/lime</b>	2020-2024		6x €4				€24
	2024-2030			3x €15	1x €30		€75
	2030-2040 <sup>59</sup>				2x €30		€60
	2040-2050						€0
<b>Electric cracking</b>	2020-2024		4x €10 + 2x €20				€80
	2024-2030			2x €40	1x €200		€280
	2030-2040						€0
	2040-2050						€0
<b>Flexible Electrically heated reactors</b>	2020-2024		4x €4				€160
	2024-2030			2x €15	1x €30		€60
	2030-2040				1x €30		€30
	2040-2050						€0
<b>Highly efficient electrical heating for ceramics</b>	2020-2024						€0
	2024-2030			3x €10			€30
	2030-2040				2x €30		€60
	2040-2050						€0
<b>Total</b>		<b>€20</b>	<b>€304</b>	<b>€185</b>	<b>€410</b>	<b>€0</b>	<b>€919</b>

#### A-3.b.5 Success factors

- Connection with **flexibility innovation programme**
- Supportive policy framework (grid, energy, tax) that aims at **enough 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)

<sup>58</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

<sup>59</sup> Could be earlier in case the economical attractiveness of this technology would improve quicker.

## A-4 Electrically driven processes

### A-4.a Electrochemical conversion

Fossil fuel is used to drive transformation in many sectors of the process industry. Thermal activation is used to drive transformations in the chemical industry, cement industry, and minerals. In other cases, 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<sub>2</sub> emissions of the process industry. Different principles can be applied to used electricity, including electrochemical, ionisation, and thermal activation.

Developing processes that use GHG emission-free electricity as the driver for the transformation instead of fossil fuels can significantly reduce GHG emissions. Electrochemistry is emerging as a technology suited for a wider range of molecular transformations across P4Planet sectors. In addition to reducing CO<sub>2</sub> emissions, other advantages of selecting electrochemical conversion can be the higher selectivity, process flexibility, or freedom of choice in the electrochemical reactor of conditions unattainable in a conventional reactor.

Electrochemical reactors can 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 can be of interest to the other sectors, albeit at a low TRL, with (for example) hydrogenation of biomass, steel production, the use of electrochemical reactors to recover non-ferrous metals from waste streams (refer to innovation programme Upgrading secondary resources in A-10.c), and in-situ production of ozone and hydrogen peroxide for water treatment.

The most important distinction between the electrochemical reactors being developed is between low temperature, largely aqueous based reactors, and high temperature reactors. Solid state high temperature reactors (based on solid oxide or proton conducting electrolytes), like those developed for hydrogen production, can be modified to carry out chemical reactors. Another high temperature reactor uses liquid as the electrolyte.

#### A-4.a.1 Innovation objectives

For electrochemical conversions, three distinguished innovation objectives are identified:

- **Low temperature aqueous electrolysis:** The existing chlor-alkali electrolyser is an example of a low temperature aqueous type. Improvements in the electrochemical process are necessary to reduce cost. For low temperature electrolyzers, key challenges include optimisation of the design of electrodes and innovative electrolyte and electrode systems that enable transformations (circumvent limits resulting from current electrode materials). There are promising electrochemical routes towards a wide range of products. This includes conversion of biobased chemicals to valuable platform chemicals, for which conversion of hydroxy methyl furfural (HMF) to furandicarboxylic acid (FDCA) is a well-known example. Other processes relevant for other sectors include (in-situ) production of hydrogen peroxide or ozone by electrochemical route. Several SPIRE projects (of which SIDERWIN is the latest) have brought the electrochemical reduction of iron oxide to iron to TRL4-5 in a low temperature (alkaline) electrolyte. Although the proposed process suffers from a large (hydrogen) by-product flow, it has been shown that CaO can be produced electrochemically from the CaCO<sub>3</sub>.
  - o Electrochemical reduction of iron ore (currently at TRL4-5).
  - o Electrochemical formation of calcium hydroxide is currently at TRL3 (MIT, 2019); this process produces H<sub>2</sub> simultaneously (using almost around 4 times as much energy), and the rationale of its application may be conditional on the possibility to use the hydrogen.
- **Solid state high temperature electrochemical reactors** can also be used to carry out other oxidation processes, such as ethylene from methane. As research shows promising

selectivity and yields, this conversion opens a thermal/electrochemical route from biogas to ethylene. Another promising application of high temperature solid state electrochemical reactors is the oxidation of propane to acrolein. These applications are currently at low TRL. For high temperature solid state of electrochemical reactors material issues (durability, performance) and scale-up of manufacturability and reactor design are key innovation areas.

- **Liquid electrolyte high temperature process:** An example of a high temperature process which works with a liquid electrolyte is the commercial process for aluminium production. Another example based on the same type of liquid electrolyte, although at a very low TRL is the high temperature route to reduce iron ore electrochemically.

Research on electrochemical production of ammonia is very promising, although production rates are orders of magnitude below what is necessary for a commercial process. Approaches towards electrochemical ammonia conversion includes all three types of electrolytic process mentioned above.

Several generic opportunities should be highlighted, (which has been taken into consideration in the programming below):

- For any of these electrochemical processes, it is beneficial when the process can be used to selectively convert specific components of a mixed feed, in which case the difference in electrochemical potential between species is used as the separating principle combining reaction and separation. A potential example of such process is the electrochemical conversion of iron oxide contained in waste flows, reducing and separating iron from other metals in a single step. Application in the non-ferrous sectors could be of interest to recover iron from red mud and ferrites from the zinc production.
- Another interesting development is the development of electrochemical processes which do not require feed in a molecular form but are able to use fine particles as feedstock. An illustration such of a process of this type is the oxidation of coal particles described in (Botte, 2014). Application on coal particles is not of interest when moving away from fossil fuels; however, the application to carbon-rich biomass waste is. Electrochemical hydrogenation of biomass can be developed to valorise low value bio-based waste streams.
- Paired synthesis, using both the anode and cathode to carry out useful reactions, is an interesting approach to reduce CAPEX cost per unit product by generating a second product.

#### A-4.a.2 Impacts

For the assumptions and methodology underlying our impact estimations reference Appendix E .

##### **Greenhouse gas emissions**

Sector	Current direct emissions in EU, MtCO <sub>2</sub>	Emissions addressed by the IP 2030, %	Emissions addressed by the IP 2050, %	Emission reduction impact 2030, MtCO <sub>2</sub>	Emission reduction impact 2050, MtCO <sub>2</sub>
Cement	102	0%	40% <sup>60</sup>	0	41
Steel	190	±1%	100%	2	190
Chemicals	124	0%	Including the electrochemical potential described in other Innovation Programs: 15% <sup>61</sup>	0	19

<sup>60</sup> With the potential to enable more GHG emission savings due to the production of hydrogen.

<sup>61</sup> Based on the reaction to produce ethylene electrochemically. With upward potential for many other chemicals (like methanol).

Sector	Current direct emissions in EU, MtCO <sub>2</sub>	Emissions addressed by the IP 2030, %	Emissions addressed by the IP 2050, %	Emission reduction impact 2030, MtCO <sub>2</sub>	Emission reduction impact 2050, MtCO <sub>2</sub>
Ceramics	20	0% (no electrochemical processes)	0% (no electrochemical processes)	0	0
Non-ferrous metals	15	1%	36% (only process emissions)	0.2	5
Minerals	19	0%	33% (lime) <sup>62</sup>	0	6
Water	0	Not determined	Not determined	0	0
<b>Total P4Planet</b>	<b>470</b>			<b>2.1</b>	<b>261</b>

## Waste

No impact on waste production, apart from contributing to impacts mentioned in innovation programme Upgrading secondary resources in A-10.c.

## Competitiveness

The competitiveness of electrochemical conversion depends on the costs for renewable electricity and on the applications.

### A-4.a.3 Programming

- Low temperature aqueous electrolysis:** Key parameters to optimise include the current density, Faradaic efficiency, electrode lifetime, overpotential. The use of scarce materials (e.g. iridium) or toxic materials (mercury, lead) must be minimised. The cost of electrodes can be significantly reduced by developing cheaper catalysts. For a wide range of processes and products, these are the generic reactor design objectives for further development: Electrochemical conversion to more complex molecules requires innovative approaches for electrode design and materials, nanostructures, and electrolyte (system)s. Catalysts and membrane materials are required to develop specific solutions for the targeted molecules. New reactor concepts that enable the effective scale-up and reduce the cost of the integrated system to the desired product (including downstream processing) should also be developed. The total amount of TRL9 projects is seven: three for chemicals (not based on CO<sub>2</sub> as these are already covered in innovation programme Catalytic conversion of CO<sub>2</sub> to chemicals/fuels in A-8.b), one for steel, one for the production of lime, one for the conversion of lignin feedstock, and one for the production of different metals (such as manganese, via electrolysis<sup>63</sup>). Current TRLs are low, apart from the steel project and the conversion of lignin feedstock.

### SPiRE project this programme builds on

**LIBERATE** uses an electrochemical approach to convert lignin feedstock (Biobased waste product) into vanillin, antioxidants, and polyamides. It leads to strong GHG reductions, waste recycling, and (at the end) cost-competitiveness and materials with some new characteristics at TRL6 with potential to go to TRL9 by 2027 with right support (e.g. NIF).

**SIDERWIN** brings a fully new electrochemical process to transform iron oxide into steel metal plates without direct CO<sub>2</sub> emissions. It is at TRL4 moving to TRL6 with further potential of TRL9 by 2030 (budget of €50 million). It will reduce GHG-emissions by 87% compared to classical steelmaking and allow 60% waste reduction due to the use of non-ferrous metallurgy residues.

<sup>62</sup> With the potential to enable more GHG emission savings due to the production of hydrogen.

<sup>63</sup> When programming (in the next paragraph), the current TRL was not known; in this table, it has been assumed that the current TRL is around 3.

- **Solid state high temperature electrochemical reactors:** Challenges to the application of high temperature solid state reactors include the design of robust reactors. Specific issues to optimising the yield include the development of a catalyst (see innovation programme Next-gen catalysis in A-9.a) and optimising electrode morphology. The challenge is to design reactors on macro, micro, and nano scale to achieve optimal conversion and contact times. Current TRL is 3-4 (depending on the process), aiming at the same programmatic development needs as for the low temperature aqueous electrolysis, but with even more emphasis on cost reduction and scale up. Additionally, the lifetime of cells operating under industrially relevant compositions is still a relatively unexplored area and is more challenging at higher temperatures. The aim is to deliver two TRL9 projects.
- **Liquid electrolyte high temperature process:**
  - To prevent the direct CO<sub>2</sub> emissions associated with the consumption of the carbon anodes during the electrolytic process, the aluminium industry investigates several options like:
    - Replacing these carbon anodes by inert anodes, as it is tested by a US/Canadian consortium under the name Elysis.
    - Using renewable bio-based carbon anodes.
    - Using CCU/CCS technology on exhaust gas from electrolysis (refer to innovation programme Flexible CO<sub>2</sub> capture and purification technologies in A-6.a).

We include in the P4Planet roadmap these innovation routes, starting at TRL 6, for the European aluminium primary producers.
  - Use of ionic liquids as electrolytes (current TRL3) offers a largely unexplored field; the aim is to develop 2 TRL9 projects.
- **A non-technological programme** is needed to solidify cross-project learnings. While electrochemical processes are different, there is an underlying shared science. The non-technological programme will focus on knowledge transfer between projects, in cooperation with national programs and related initiatives at European scale (including the FCH JU). This requires around €300,000 per year over a period of 8 years, mainly between 2024 and 2030.

#### A-4.a.4 Investment needs

Table 11: Investment needs in € million<sup>64</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Low-temperature aqueous electrolysis</b>	2020-2024		10x €5	2x €10			€70
	2024-2030			5x €10	2x €60 (iron+lignin)		€170
	2030-2040				5x €60		€300
	2040-2050						€0
<b>Solid state high temperature electrochemical reactors</b>	2020-2024		6x €5				€30
	2024-2030			2x €20			€40
	2030-2040				2x €100		€200
	2040-2050						€0
<b>Liquid electrolyte high temperature process</b>	2020-2024		6x €5	2x €20			€70
	2024-2030			2x €20	2x 100 (Al)		€240
	2030-2040				2x €100		€200
	2040-2050						€0

<sup>64</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Non technological</b>	2020-2024					2x €0,3	<b>€0.6</b>
	2024-2030					6x €0,3	<b>€1.8</b>
	2030-2040						<b>€0</b>
	2040-2050						<b>€0</b>
<b>Total</b>		<b>€0</b>	<b>€110</b>	<b>€190</b>	<b>€1,020</b>	<b>€2</b>	<b>€1,322</b>

#### A-4.a.5 Success factors

- Must use cheap, abundantly available renewable electricity.
- Electro organic synthesis or electrochemical conversion of hydrocarbons needs to transform from a niche technology to a common synthetic method. Therefore, electrosynthesis also must find its place in teaching and student training. The sustainability of this approach will make its use 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 required, partially solid, liquid, gas,), 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 so infrastructure for recycling is required.

## A-4.b Electrically driven separation

### A-4.b.1 Innovation objectives

Significant amounts of thermal energy are used for separation. Electrically driven separation could separate using considerably lower amounts of energy for the same functionality in the form of GHG emission-free electricity. To this end, a toolbox of technologies with several innovation objectives needs to be developed. The 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 electro dialysis and membrane capacitive deionisation, are not used for bulk processes because they are not cost-competitive. Other technologies of interest for the water sector include electrochemical precipitation and electrocoagulation. Largely unexplored is the use of electrical and magnetic fields to influence properties and behaviour of materials, such as the hydrophobicity or the induced magnetic forces, as a principle for separation.
  - Although electro-separation technologies are not used at wide scale over the whole process industry, increased demand for the 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, or reverse osmosis 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, but it will also be useful for future applications. 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 be applied to several applications:

- **Near zero-water-discharge-plant:** Minimising the use of fresh water in processes and by closing the water loop 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. These streams typically contain multiple impurities (such as salts and organic residues) making separation more complex.
- **Reduce cost of downstream separation for bio-based processes:** 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 bio-based processes. The objective is to reduce downstream processing costs 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 based on volatility. These processes are typically energy intensive (for example ethane/ethylene in a steam cracker), and significant amounts of energy can be saved with electrically driven separation technologies.
- **Valorisation of gaseous combustible waste streams** can be present in installations in the chemical industry and refineries, but also in for example steel plants (CO/H<sub>2</sub>) or using

CO to pre-reduce minerals in a pre-treatment unit. Better separation allows more high value application of the valuable components.

#### **A-4.b.2 Impacts**

For the assumptions and methodology underlying our impact estimations reference Appendix E .

##### ***Greenhouse gas emissions***

**Near zero-water-discharge-plant:** This saves electricity consumption, but because that is all GHG emission-free in 2050, the GHG emissions savings are zero. The large buffering ponds offer the potential for flexibility in use (demand side management).

**Replace thermal distillation:** Chemicals: 50% of the chemical industry's energy use is in separation (distillation plus absorption; 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:** 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). These savings are 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.

Combined, the GHG emissions impact are estimated to be 12% in the chemicals sector in 2050, and only very limited in 2030. With 124 MtCO<sub>2</sub> emissions, this represents 15 MtCO<sub>2</sub> reductions in 2050. For non-ferrous metals, very limited emission reductions are expected (below 5%). The impact is not quantified for the water sector.

##### ***Waste***

- **Near zero-water-discharge-plant:** Full prevention of wastewater discharge; quantity off valorised components in wastewater: Not known.
- **Other applications:** No impact.

##### ***Competitiveness***

**Near zero-water-discharge-plant:** Developing these technologies helps make meeting the goal of zero discharge of wastewater achievable at a lower cost.

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

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

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

#### **A-4.b.3 Programming**

A toolbox of technologies, including membrane technologies, must be developed for this innovation programme. The toolbox can be applied to a variety of applications (refer to the innovation objectives). Currently, these technologies are at various TRLs. For many technologies, it would take around 10 years to bring them to TRL7 and another 5 years to bring them to TRL9 (relatively short as these are modular systems). A whole-system approach (design, engineering, production, and testing) needs to be followed to bring these technologies to TRL9.

For each technology brought to TRL9, a non-technological component needs to be added to ensure the following:

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

#### A-4.b.4 Investment needs

Table 12: Investment needs in € million<sup>65</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Electrically (magnetic) driven separation</b>	2020-2024		6x €5	1x €35			<b>€65</b>
	2024-2030		4x €5	2x €35	3x €50		<b>€240</b>
	2030-2040			2x €35	2x €50	3x €2	<b>€176</b>
	2040-2050					3x €2	<b>€6</b>
<b>Total</b>		<b>€0</b>	<b>€50</b>	<b>€175</b>	<b>€250</b>	<b>€12</b>	<b>€487</b>

#### A-4.b.5 Success factors

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

<sup>65</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-5 Hydrogen integration

This innovation area focuses on the implementation of GHG emission-free hydrogen into the process industries. 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 if the carbon for the reduction step will be replaced by hydrogen. GHG emissions of the current production need to be reduced to zero.

This innovation area covers three innovation programmes:

- **Alternative hydrogen production routes:** The two most-explored routes towards hydrogen production 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:  $2 \text{H}_2\text{O} - 2 \text{H}_2 + \text{O}_2$ ). We assume that development of these two production routes will be included in the Fuel Cells and Hydrogen Joint Undertaking and thus do not focus on these production routes. Several alternative hydrogen production routes are developed as well; their development needs are covered in innovation programme Alternative hydrogen production routes (A-5.a).
- **Using hydrogen in industrial processes:** Hydrogen's use as an 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 Using hydrogen in industrial processes (A-5.b).
- **Hydrogen storage:** Because some of the new production routes of hydrogen use renewable electricity, which production depends on the variable availability of wind or sun, there will be a benefit to storing hydrogen. This is described in innovation programme Hydrogen storage (A-5.c).

## A-5.a Alternative hydrogen production routes

This innovation programme explores alternative hydrogen production technologies. Blue and green hydrogen are not in scope because they are addressed in other initiatives.

### A-5.a.1 Innovation objectives

Next to blue and green hydrogen, the technologies that follow can play a role in the future production of hydrogen with lower or no GHG emissions:

- **Pyrolysis of methane:** A process technology that produces hydrogen from natural gas, as well as biogas, landfill gas, or synthetic methane. This technology splits natural gas directly into its hydrogen and carbon components. Methane pyrolysis follows the reaction  $\text{CH}_4 \rightarrow \text{C} + 2 \text{H}_2$ ; 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 aluminium 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 GHG emission-free sources, hydrogen can be produced on an industrial scale without GHG emissions.
- **Photoelectrocatalysis (PEC):** This process directly converts solar energy into the energy required for the decomposition of water. PEC cells operate at ambient pressure and temperature and at lower potentials than electrolysis which makes PEC more energy efficient. Furthermore, PEC decouples  $\text{H}_2$  production from external electric input, which make  $\text{H}_2$  production independent from natural gas and electricity costs.
- **Thermochemical/thermochemical 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 a high temperature by stripping oxygen.
- **Electrochemical  $\text{H}_2\text{S}$  splitting:** Hydrogen can also be produced from  $\text{H}_2\text{S}$  using similar technologies (electrolysis and photoreactors) to the production of green hydrogen from water.  $\text{H}_2\text{S}$  is a by-product of refineries and natural gas processes,<sup>66</sup> and with bifunctional hydrogen generators can process  $\text{H}_2\text{S}$  and water as a feedstock. This  $\text{H}_2\text{S}$  is converted using the Claus-process (converting  $\text{H}_2\text{S}$  into  $\text{H}_2\text{O}$  and S); the production of S (sulphur) does not change and can be used in various markets. The key impact is that with this process hydrogen is produced instead of water.
- **Bio-based production of hydrogen (gasification of biomass):** Biomass gasification produces hydrogen using steam. With suitable gas cleaning technology and separating off  $\text{CO}_2$  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 integrated into a wider bioeconomy, enhancing the valuable components from the biomass and then gasifying the remaining parts.

### A-5.a.2 Impacts

For the assumptions and methodology underlying our impact estimations reference Appendix E .

#### **Greenhouse gas emissions**

These technologies lead to the following GHG emission reduction:

- Pyrolysis of methane: Maximum 0,26 t  $\text{CO}_2$ /t  $\text{H}_2$  (DECHEMA & FutureCamp, 2019) from the production of methane<sup>67</sup> (reduction: 97%).
- Photoelectrocatalysis: Up to 95%.
- Thermochemical/Thermochemical water splitting: Up to 95% if the energy requirements are supplied by solar energy.

<sup>66</sup>  $\text{H}_2\text{S}$  splitting can thus be considered as the electrification of the desulfurisation process in these industries.

<sup>67</sup> Total GHG effect will depend on the use and end-of-life treatment of the by-product solid C.

- Electrochemical H<sub>2</sub>S splitting: Compared to the Claus process, the H<sub>2</sub>S process does not emit GHG, leading to hydrogen production with 100% reduction of GHG emissions. The overall GHG emission reduction is even higher, as the Claus process that it replaces also emits some GHGs (in the incinerator where remaining, nonconverted, H<sub>2</sub>S is converted to SO<sub>2</sub> using natural gas).
- Gasification of biomass: Depending on the accounting method, gasification of biomass can reduce 100% of emissions. When the CO<sub>2</sub> produced is captured and stored or used it could reduce more than 100%.

This reduction could be applied to the full production of hydrogen (now around 10 Mt/year in Europe (FCH JU, 2019)), leading to emission reductions of around 100 MtCO<sub>2</sub>/year.<sup>68</sup> This is partially in the P4Planet sectors and partially in other sectors (e.g. refineries).

In the future, the process industry will likely use more hydrogen (see the next innovation programme, and for the production of fuels/chemicals/polymers with CCU), and this is anticipated to increase the significance of alternative hydrogen production routes, including blue and green hydrogen. The technologies programmed here are expected to have deployment impact after 2030, apart from biomass gasification, of which the TRL9 project is programmed to be executed from 2020 to 2024. Assuming 10% deployment, the 2030 impact would be 10 MtCO<sub>2</sub>.

### **Waste**

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

- Pyrolysis of methane: Solid carbon is formed as a by-product. If this can not be sold for applications then the excess solid carbon needs to be stored, which is not in line with P4Planet's no landfilling ambition for 2050. Therefore, it is key that all by-product can be sold to other markets in which it does not lead to landfilling/GHG emissions.
- Photoelectrocatalysis: No waste produced.
- Thermochemical/Thermoelectrochemical water splitting: No waste is produced.
- Electrochemical H<sub>2</sub>S splitting: The sulphur produced is used the production of several compounds as sulfuric and sulphydric acids, carbon sulphides, 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 emphasise the potential competitiveness of these alternative hydrogen production routes, hydrogen production costs are estimated here. These high level estimations are uncertain because technology developments may deliver different costs, and because lower electricity prices are key drivers for costs in many cases.

#### **Pyrolysis of methane**

Table 13 compares the hydrogen production cost by pyrolysis of methane to steam methane reforming. The table shows that under these assumptions and without taking benefits from by-products into account, pyrolysis would be more expensive than hydrogen from steam methane reforming (SMR). However, the sales of the resulting carbon black would make it more competitive. Three tonnes of carbon black are produced for each tonne of hydrogen, so pyrolysis would be competitive at carbon black prices of around €480/tonne with carbon price of €25/tCO<sub>2</sub>

<sup>68</sup> Assuming that all H<sub>2</sub> is produced by SMR (in reality: 95%) and a ratio of 9,7 t CO<sub>2</sub> /t H<sub>2</sub> produced with that technology.

and €95/tonne with carbon price of €150/tCO<sub>2</sub> under these assumptions. Additionally, lower electricity prices and higher carbon prices also boost the competitiveness of pyrolysis.

**Table 13: Competitiveness of pyrolysis of methane compared to SMR<sup>69</sup>**

Parameter	Unit	SMR at €25/tCO <sub>2</sub>	SMR at €150/tCO <sub>2</sub>	Pyrolysis at €25/tCO <sub>2</sub>	Pyrolysis at €150/tCO <sub>2</sub>
<b>CAPEX - annuitised</b>	EUR/tH <sub>2</sub>	333	333	449	449
CAPEX	EUR/tH <sub>2</sub> /yr			4,080	4,080
CRF	%			11.02%	11.02%
<b>OPEX</b>	EUR/tH <sub>2</sub>	1,542	2,729	2,866	2,898
<b>Fuel costs</b>	EUR/tH <sub>2</sub>	1,523	1,523	2,859	2,859
Gas consumption	tCH <sub>4</sub> /tH <sub>2</sub>	3	3	4.5	4.5
Gas price	EUR/t CH <sub>4</sub>	508	508	508	508
Energy density	GJ/t CH <sub>4</sub>	54	54	54	54
Gas price	EUR/GJ	9.40	9.40	9.40	9.40
Electricity consumption	MWh/tH <sub>2</sub>			10.12	10.12
Electricity price	EUR/MWh	56.80	56.80	56.80	56.80
<b>Carbon costs</b>	EUR/t H <sub>2</sub>	237.5	1425	6.5	39
CO <sub>2</sub> emissions	tCO <sub>2</sub> /t H <sub>2</sub>	9.5	9.5	0.26	0.26
Carbon price	EUR/tCO <sub>2</sub>	25	150	25	150
<b>Sales steam</b>	EUR/t H <sub>2</sub>	-218.82	-218.82	0	0
Value of steam	EUR/t by-product	31.26	31.26		
Quantity of steam	tonne/tH <sub>2</sub>	7	7		
<b>Total costs</b>	EUR/tH <sub>2</sub>	1,875	3,063	3,315	3,348
<b>Total costs</b>	EUR/kgH <sub>2</sub>	1.88	3.06	3.32	3.35

### Photoelectrocatalysis

The annuitised CAPEX for PEC are estimated to be about €1,900/tonne hydrogen (i.e. €1.9/kg). OPEX are negligible. Other studies estimate a production cost of €2.1-€2.3/kg hydrogen for fully developed technology (DOE, 2012). At this cost level it would be roughly competitive to SMR at €25/tCO<sub>2</sub> (see Table 13) and more competitive than SMR at higher carbon prices.

### Thermochemical/thermoelectrochemical water splitting

The annuitised CAPEX of this technology is estimated to be between €600 and €650/tonne hydrogen per year (FCH JU, 2013). OPEX are expected to be around €3/kg hydrogen (it is unclear which part is formed by electricity costs and what the used electricity price is). Combined, this would amount around €3.6/kg hydrogen. This price would not be competitive with SMR at a carbon price of €150/tCO<sub>2</sub> (see Table 13). The breakeven carbon price is around €210/tCO<sub>2</sub>. Lower electricity prices would result in a lower breakeven carbon price.

### Electrochemical H<sub>2</sub>S splitting

The annuitised CAPEX for this technology is assumed to be 2.5 times the CAPEX of SMR, or €833/tonne hydrogen. The CAPEX depends on the materials used in the electrodes (platinum or not). With estimated electricity consumption of 25 MWh/tonne hydrogen and the default electricity price of €56.8/MWh, energy costs would be €1,420/tonne hydrogen. Total production costs for hydrogen are estimated to be around €2.3/kg. This is slightly above the estimated production costs using SMR under a €25/tCO<sub>2</sub> carbon price and below estimated SMR production costs under a €150/tCO<sub>2</sub> carbon price. Considering that the sulphur recovery units (Claus process) that convert the H<sub>2</sub>S into S<sub>2</sub> and H<sub>2</sub>O are no longer needed, additional CAPEX savings are expected, which might make it already competitive at a €25/tCO<sub>2</sub> carbon price.

### Gasification of biomass

<sup>69</sup> The values in this table are based on expert estimates for SMR, and for pyrolysis they are based on (DECHEMA & FutureCamp, 2019) and (BASF & Institute of Thermodynamics, 2018)

The CAPEX for a gasification unit is expected to be in the range of €2 million for an installed capacity of 1 MW biomass input. Assuming 8,760 load hours and an energy density of 120 GJ/t hydrogen, this translates into €7,610/tonne hydrogen. The biomass (wood) demand is 17 tonne wood/tonne hydrogen. Assuming a price of €4/GJ waste biomass (shredded from forest, by-products from wood processing), the fuel costs are €1,165/tonne hydrogen. Total hydrogen production costs would be €2/kg under these assumptions. Under a €25/tCO<sub>2</sub> carbon price gasification would be competitive with SMR when wood is priced at €61/tonne, and under a €150/tCO<sub>2</sub> carbon price it would be competitive at €130/tonne wood. The technology has the potential to be competitive.

This high-level analysis shows that the alternative hydrogen production technologies could be competitive under different circumstances, and all offer a real potential. Therefore, all technologies are programmed in parallel.

### A-5.a.3 Programming

- **Pyrolysis of methane:** Expect 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 include the following:
  - Need for basic R&D and new reactor design
  - Need for heating concept to overcome the low radial heat transfer from the wall into the reactor core
  - Manage inhomogeneous flow and pulsations
  - Require high temperature materials
  - Apply three potential technologies:
    - Liquid metal technology
    - Catalytic thermal cracking (challenges to overcome: Fast deactivation of the catalysts and management of spent catalysts)
    - Plasma-arc technologies
- **PEC** is still at an early R&D phase. Groups are aiming to develop technologies (different catalysts, electrodes, using concentration of solar radiation, varying the position of mirrors), with current TRLs ranging from 2-3 to 4-5. Development aims at achieving:
  - Increased stability and lifetime of the electrodes
  - Discovery or development of suitable photoelectrodes and photocatalyst
  - Optimisation of reactor design
  - Solar to hydrogen conversion efficiency of >20%
  - Reducing the CAPEX cost by reducing PEC module costs <100 €/m<sup>2</sup> (since the technology is CAPEX intensive, representing around 80%-90% of total costs)
  - The non-technological investment needs concern regulatory, standardisation, awareness, and educational issues
  - This only includes the PEC where hydrogen is produced, and excludes technologies that bind it directly to carbon
- **Thermochemical/thermochemical water splitting**
  - Thermochemical and hybrid cycles need small MW range prototype demonstrations. The technology needs to go from TRL5-6 to TRL7.
  - Investigate the use for high temperature industrial waste heat.
  - Develop efficient and robust reactor designs compatible with high temperatures and heat cycling.
  - Increase efficiency and durability.
- **Electrochemical H<sub>2</sub>S splitting**
  - H<sub>2</sub>S electrolysis currently is at TRL4, it needs to be at TRL6 by 2030.
  - A demo for refinery and natural gas process units is needed in 2040-2050.
  - Non-Pt group electrocatalyst is currently at TRL2 and needs to be at TRL5. Initially, the platinum group electro-catalyst can be used and later replaced by non-Pt electro-catalyst to lower OPEX.

- **Bio-based production of hydrogen (gasification of biomass):**
  - There are existing biomass gasification plants of 10 MW scale. The important topic is cleaning of syngas and separation of the hydrogen formed. There is potential optimisation (gasification of the char with oxygen [for example, from electrolyzers], which creates CO<sub>2</sub> that can be stored and leads to negative emissions).

When developing these technologies, the overall sustainability of the processes needs to be assessed from a system perspective, including considering by-products and waste.

Other alternative hydrogen production routes could be developed as well.

#### A-5.a.4 Investment needs

Table 14: Investment needs in € million<sup>70</sup>

Activity	Timing	TRL1 -3	4-6	7-8	9	Non- technol ogical	Total
<b>Pyrolysis of methane</b>	2020-2024		3x €10 (TRL4-5) (2020-2023)				€30
	2024-2030			1x €50 (TRL5-7) (2023-2027)	1x €100 (TRL7-9) (2027-2031)		€150
	2030-2040						€0
	2040-2050						€0
<b>Photoelectro-catalysis</b>	2020-2024	6x €2.5	2x €10			2x €1	€37
	2024-2030		2x €10	1x €25			€45
	2030-2040			1x €25	1x €150	2x €1	€177
	2040-2050				1x €150	1x €1	€151
<b>Thermochemical / Thermo-electrochemical water splitting</b>	2020-2024		2x €12				€24
	2024-2030			1x €20			€20
	2030-2040				1x €100 (2035)		€100
	2040-2050						€0
<b>Electrochemical H<sub>2</sub>S splitting</b>	2020-2024	5x €2	2x €8			2x €1	€28
	2024-2030		2x €8	1x €20			€36
	2030-2040			1x €20	1x €120	2x €1	€142
	2040-2050				1x €120	2x €1	€122
<b>Gasification of biomass</b>	2020-2024				2x €35		€70
	2024-2030						€0
	2030-2040						€0
	2040-2050						€0
<b>Total</b>		<b>€25</b>	<b>€126</b>	<b>€160</b>	<b>€810</b>	<b>€11</b>	<b>€1,132</b>

#### A-5.a.5 Success factors

- Pyrolysis of methane:

<sup>70</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

- Carbon collection system (separation of the fine carbon particulate matter from the gas stream).
  - Costs and lifetime of the plasma system.
- Photoelectrocatalysis:
  - Solar to hydrogen efficiency >20%.
  - PEC module costs <100 €/m<sup>2</sup> (since the technology is CAPEX intensive, representing around 80%-90% of total costs).
- Thermochemical/Thermoelectrochemical water splitting (DOE, 2012):
  - Solar to hydrogen (STH), energy conversion ratio of 26%.
  - Cycle time of 1 min/cycle.
- Electrochemical H<sub>2</sub>S splitting:
  - The energy price (electricity) should be below €0.2/kWh. Then H<sub>2</sub>S 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.

## A-5.b Using hydrogen in industrial processes

This programme focuses in the need of retrofitting or complete changing the different processes of the industry where the low carbon hydrogen could be used.

### A-5.b.1 Innovation objectives

This innovation programme covers a couple of innovation objectives:

**Combustion in furnaces** can be improved in two manners:

- **By using hydrogen rather than fossil fuels:** When hydrogen is produced without GHG emissions, replacing fossil fuels (such as natural gas or coal) with hydrogen eliminates the GHG emissions. Currently used furnaces are often not equipped to use hydrogen, as:
  - Different 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 sulphur-containing fossil fuel is used)
  - Different steel types may be needed (not all used steel may be suitable for hydrogen)
  - Measurement and control instrumentation are necessary to detect and regulate fuel gas characteristics and flows because, up to now, it is not possible to handle variable compositions with sufficient accuracy
- **By using oxygen rather than air:** When green hydrogen is used, or when a green hydrogen plant is nearby 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 formed in the hydrogen production for DRI would be needed in the steel industry. The other 85% would become available for other applications. Using oxygen rather than air leads to:
  - A higher temperature
  - Other off-gas temperatures
  - Smaller air separation units/compressors

**Using hydrogen in the steel industry:** There are two manners in which hydrogen can be introduced as a reducing agent:

- Integrate decentralised hydrogen production in a **classical integrated** BF/BOF or DR/EAF steel plant and combine the hydrogen with other process gases in the process chain steps
- Develop **new process concepts** for steelmaking based on hydrogen and alternative raw materials (such as waste, loose iron and by-products [including fines]). This includes making steel directly from iron oxides without intermediate stages, using a hydrogen plasma technology to reduce the iron oxides and to melt the metallic iron, and opening up fundamentally new possibilities of alloying of different high quality steel grades.

**Using hydrogen in the non-ferrous metals industry:**

- Hydrogen can be used as a reducing agent for some pyro smelting processes (e.g. copper),<sup>71</sup> aluminium, in ferro-alloys, and in the recovery of metals from smelting slag or leaching residues (Wyns & Khandekar, 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

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<sup>71</sup> Smelters already requiring a lot of O<sub>2</sub> might have better business case for use of H<sub>2</sub> via electrolysis, which has O<sub>2</sub> as a by-product.

also be developed. These include (the other CCU-routes to produce fuels, chemicals, and polymers are described in other innovation programmes):

- The use of hydrogen to bring biomass or waste to the right C/H/O ratio for applications (fuels and chemicals).
- Ammonia, which can for example be produced by reacting no emission hydrogen with nitrogen. Produced ammonia can be used for:
  - Its current applications, mainly as fertiliser.
  - New applications of ammonia in furnaces and in gas turbines: Ammonia can be directly used as an energy carrier and partly replace the fossil energy sources used in industrial processes by directly using ammonia in furnaces, gas turbines, or even fuel cells. In recent years, there have been different initiatives including those of Tohokou University, AIST, and Toyota Energy Solutions to develop a 100% 300 kW ammonia turbine. There are also initiatives to develop fuel cells between 1 W and 100 kW. The critical point is to minimise NOx emissions and to avoid non-combusted ammonia, which can lead to the formation of particulate matter (an air pollutant) and acidification. It is necessary to continue with the scaling and development of the technology that allows working with 100% ammonia.
- Methanol, which can be produced by reacting no emission hydrogen with CO<sub>2</sub>.
- The side-product oxygen (from the generation of hydrogen using electrolysis) can be used for oxidation reactions (for example, the generation of nitric acid or as oxidising agent in processes like water treatment, or to improve the efficiency and the business case of some technologies like gasification of biomass or waste, or in fermentation reactions where large amounts of air are often used).

### **A-5.b.2 Impacts**

For the assumptions and methodology underlying our impact estimations reference Appendix E . The following section includes the 2050 impacts as most innovations are not deployed by 2030 (unless stated otherwise).

#### **Greenhouse gas emissions**

##### *Improving combustion in furnaces using hydrogen*

- The impact of replacing the furnaces fuel by GHG emission-free hydrogen is 100% when fully applied:
  - Cement industry: All fossil fuel related emissions are 41 MtCO<sub>2</sub>.
  - Steel industry: Maximum 10%, heating and annealing furnaces, but not the primary steelmaking processes, so all targeted GHG emissions amount to 19 MtCO<sub>2</sub>.
  - Chemical industry: Naphtha crackers emissions are about 25%<sup>72</sup>, so maximum potential is 31 MtCO<sub>2</sub>.
  - Ceramics industry: Up to 10% of fossil fuel related emissions are below 500°C depending on how the furnaces are fired; so up to 1.6 MtCO<sub>2</sub> can be reduced.
  - Non-ferrous metals: H<sub>2</sub> as fuel can replace fossil fuels for heating purposes. Potential emission reduction of 7.5%-10% of the sector's scope 1 emissions, with cross-sectorial innovations needed in burner design; about 1 MtCO<sub>2</sub>.
  - Lime industry: About 100% of fossil fuel related emissions can be reduced; 6 MtCO<sub>2</sub>.
  - Refineries industry: 30-50%, depending of the refinery scheme.
- Limited impact in 2030.

##### *Improving combustion in furnaces using oxygen*

- The fuel saving attainable due to the elimination of the need to heat nitrogen can be around 25% (if there is no heat recovery) or higher (due to productivity increases and the reduced need for excess air [based on (Henderschot, Lebrecht, & Easterbrook, 2010)]). There will be

<sup>72</sup> Estimate based on the share of GHG emissions coming from the production of High Value Chemicals, relative to the overall sector's GHG emissions excluding nitric acid – which has largely be abated – using data > 10 years old (Ecofys, 2009).

some degree of heat recovery in most furnaces, so the fuel (and thus emissions) savings are likely in the order of magnitude of a couple of percent.

- Limited impact in 2030.

#### *Using hydrogen in the classical integrated steel production*

- Up to 30% in the BF/BOF route in 2050, up to 3% in the BF/BOF route in 2030; if BF/BOF is 90% of fossil fuel-related emissions, this amounts to 51 MtCO<sub>2</sub> in 2050 and 5 MtCO<sub>2</sub> in 2030.

#### *Using hydrogen with new process concepts in the steel industry (DR/EAF)*

- More than 80% of emissions can be reduced (assuming some natural gas would still be needed). This implies that 100% emission reduction would be feasible in combination with using biogas for the remaining fuels.
- Impact only after 2030.

#### *Using hydrogen in the non-ferrous metals industry*

- Potential to reduce emissions in the production.

#### *Using hydrogen in the chemical and refining industry*

- GHG emissions, when GHG emission-free hydrogen is used:
  - Ammonia production: -100% emissions, applied to 22% of the chemical industry's GHG emissions.<sup>73</sup> This amounts to 27 MtCO<sub>2</sub>.
  - Methanol: -100% of emission, applied to <10% of the chemical industry's GHG emissions<sup>74</sup> (CCU process, not just replacing emissions from the plant, but also producing emission free methanol). This amounts to 12 MtCO<sub>2</sub>.
  - Rest of chemical industry: 100% of the emissions from hydrogenation reactions, which are estimated to be less than 10% of the remaining emissions.
  - Refinery: 20% of emissions of total refinery are from hydrogen production, this can be eliminated.
- Limited impact in 2030.

Overall, the impacts total 285 MtCO<sub>2</sub> in 2050 and 5 MtCO<sub>2</sub> in 2030.

## **Waste**

- No impact; Less pollution to the environment from the cokes oven plant when moving to DR/EAF. However, as this waste is used within the process, this is more of an efficiency effect.

## **Competitiveness**

- Need cheap green hydrogen (technology development, electricity, policies, or other technologies delivering cheap no-emission hydrogen)
- Improved energy efficiency (less fuel [for example, hydrogen] is needed, and there are lower investment needs for heat recovery equipment) can improve the competitiveness, although it is an expensive technology.

### **A-5.b.3 Programming**

The following programmes have been identified:

- **Improving combustion in furnaces by using hydrogen rather than fossil fuels:** This technology is currently at TRL5. Further development is needed for the new burner types, adjustments in the combustion system, conductive zone of the furnace, and the (off-)gas system.
- **Improving combustion in furnaces by using oxygen rather than air:** This technology is not at the higher TRL. Development focuses on the temperature changes, the reduced volumes that need to be separated, and the intermittent availability of oxygen.

<sup>73</sup> Using (Ecofys, 2009), ignoring the nitric acid and adipic acid related emissions.

<sup>74</sup> Using (Ecofys, 2009), ignoring the nitric acid and adipic acid related emissions.

- **Using hydrogen in the classical integrated steel production:** A FOAK demonstration project is needed for the combination of H<sub>2</sub> production, grid stabilisation, and integrating these with the energy system of the steel plant (for example by supplying residual heat to a high temperature hydrogen electrolyser).
- **Using hydrogen with new process concepts in the steel industry:** Process concepts for the reduction of iron ore fines and waste materials will be developed from TRL4-7. This is also true for hydrogen plasma smelting reduction and for process development from batch operation to continuous operation.
- **Using hydrogen in the non-ferrous metals industry** for heating. Concepts for the integration of hydrogen in the reduction and smelting process of primary and secondary raw material sources in non-ferrous metals production has to be developed starting from TRL 4 to higher levels.
- **Integrating hydrogen as a feedstock in the chemical and refining sector:** (FOAK) demonstration projects are necessary for the integration of these new technologies in chemical processes (and in refineries) and for managing the new raw materials for the hydrogen production process and the new by-products derived from it.

#### A-5.b.4 Investment needs

Table 15: Investment needs in € million<sup>75</sup>

Activity <sup>76</sup>	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Improving combustion in furnaces – using hydrogen</b>	2020-2024			5x €7.5 <sup>77</sup>			€37.5
	2024-2030				5x€30		€187.5
	2030-2040						€0
	2040-2050						€0
<b>Improving combustion in furnaces – using oxygen</b>	2020-2024			5x €7.5			€37.5
	2024-2030				5x€30		€150
	2030-2040						€0
	2040-2050						€0
<b>Using hydrogen in the classical integrated steel production</b>	2020-2024				3x €50 <sup>78</sup>		€150
	2024-2030						€0
	2030-2040						€0
	2040-2050						€0
<b>Using hydrogen in the steel industry - new process concepts</b>	2020-2024			3x €30			€90
	2024-2030			3x €50			€150
	2030-2040				6x €100		€600
	2040-2050						€0
<b>Using hydrogen in the non-ferrous metals industry</b>	2020-2024		9 x €10				€90
	2024-2030			3x € 25			€75
	2030-2040				3x €50		€150
	2040-2050						€0
	2020-2024			5x €35			€175

<sup>75</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

<sup>76</sup> Cost exclude the cost for electrolyzers.

<sup>77</sup> Average of range of €5-10 million

<sup>78</sup> Allows the development for three different concepts in iron/steelmaking route.

Activity <sup>76</sup>	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Using hydrogen in the chemical and refining industry	2024-2030				5x €40 <sup>79</sup>		€200
	2030-2040						€0
	2040-2050						€0
<b>Total</b>		€0	€90	€603	€1,400	€0	€2,092.5

### A-5.b.5 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 levels, green hydrogen's role can help gain recognition and legislation that introduces a clear methodology (such as mass balancing) to account for green hydrogen's use in chemical processes is needed to support its introduction.

<sup>79</sup> 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 TRL7-8.

## A-5.c Hydrogen storage

The hydrogen produced from renewable electricity may not always be available in constant quantities. In periods of availability of excess renewable electricity, hydrogen can be converted to natural gas, or other fuels. Apart from ammonia, these fuels are treated in the CCU innovation areas. Alternatively, the hydrogen consuming production processes could slow down production. The direct storage of hydrogen (a task in this innovation programme), enables constant availability of hydrogen for the process industry. This section describes the innovations required for hydrogen storage and for the use of ammonia as a hydrogen carrier.

### A-5.c.1 Innovation objectives

This programme will focus on:

- **Storage of hydrogen:** Developing a system to store excess renewable energy is a priority, and direct storage of hydrogen is one of the options. Hydrogen storage's success is key to the transformation of the fossil-based energy system to renewables. Only large-scale storage can solve the storage problem presented by the process industry's fluctuating renewable energy and continuous hydrogen supply. Hydrogen can be directly stored in underground natural gas storage areas, and in depleted oil & gas fields or salt caverns. For the recovery process (for example, from natural gas storage), separation technologies for natural gas and hydrogen are necessary.
- **Development of alternative hydrogen carriers:** Hydrogen has a relatively large compressibility factor and low boiling point, and its compression and liquefaction consume energy. For large-scale storage and long-distance transportation, carriers of high hydrogen and energy densities are of equivalent importance than hydrogen. Ammonia is a suitable hydrogen carrier (ammonia infrastructure is well established, and ammonia can be reconverted to hydrogen and nitrogen). Other hydrogen carriers have also been developed, mainly liquid organic hydrogen carriers (LOHC; for example, toluene) and methanol. The latter is covered under the innovation programme Catalytic conversion of CO<sub>2</sub> to chemicals/fuels (A-8.b).

### A-5.c.2 Impacts

For the assumptions and methodology underlying our impact estimations reference Appendix E.

#### **Greenhouse gas emissions**

Hydrogen produced by several technologies on a continuous or a fluctuating operation can be compressed and stored underground in different existing installations. Storage enables hydrogen's use but has no direct savings impact: When hydrogen storage is driven by GHG emission-free electricity, it does not cause any GHG emissions.

#### **Waste**

No waste is produced during the storage of hydrogen.

#### **Competitiveness**

Hydrogen storage increases cost so to maintain competitiveness the cost increase needs to be as low as possible. This large storage option allows the shifting of excess renewable energy (for example, from summer season to winter season). Thus, energy shifting also effects the competitiveness of renewable energy, as it prevents shutting down installations during periods with low energy demands and high production.

### A-5.c.3 Programming

Storage and recovery technology must be demonstrated in an industrial scale with real renewable energy generation:

- For storage of hydrogen: The technology is currently at TRL5-6; for hydrogen storage in natural gas fields, (membrane) technologies that separate hydrogen from the natural gas

when recovering the hydrogen need further development. For hydrogen storage in caves or depleted gas fields, additional understanding of reactions with materials and their tightness (geology) is necessary.

- For ammonia as a hydrogen carrier: The technology of cracking or dehydrogenation of ammonia to hydrogen and subsequent purification of hydrogen is in TRL6-7. The catalysts used in the cracking process and in the subsequent phase of hydrogen purification to eliminate possible traces of ammonia need to be further developed.
- For other hydrogen carriers the programming (TRL, project investment needs) is based on ammonia as a hydrogen carrier. Three other hydrogen carriers (mainly LOHC) are assumed.

#### A-5.c.4 Investment needs

Table 16: Investment needs in € million<sup>80</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Hydrogen storage</b>	2020-2024		3x €25	2x €15			<b>€105</b>
	2024-2030			2x €40	2x €20		<b>€120</b>
	2030-2040				2x €60		<b>€120</b>
	2040-2050						<b>€0</b>
<b>Hydrogen carriers</b>	2020-2024			4x €15			<b>€60</b>
	2024-2030				4x €40		<b>€160</b>
	2030-2040						<b>€0</b>
	2040-2050						<b>€0</b>
<b>Total</b>		<b>€0</b>	<b>€75</b>	<b>€170</b>	<b>€320</b>	<b>€0</b>	<b>€220</b>

#### A-5.c.5 Success factors

- Hydrogen, ammonia, and other storage implementation will go hand-in-hand with the development of the hydrogen economy and the increase of variable electricity generation. Storage is a success factor for the transformation of the energy system, rather than the other way around.

<sup>80</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-6 CO<sub>2</sub> capture for utilisation

### A-6.a Flexible CO<sub>2</sub> capture and purification technologies

Flexible carbon capture and purification technologies are necessary for the separation of CO<sub>2</sub> from industrial flue and process gases. The aim is to develop flexible, modular, energy efficient and cost-efficient capture and purification technologies that enable storage. Storage needs to be enabled for deep emission cuts and valorisation of CO<sub>2</sub> by exploiting CO<sub>2</sub> as a carbon source in e.g. fuels and chemicals. Technology development is needed to enable deep emission cuts from the industry towards 2030 and 2050. The objective is to develop technologies that lower the threshold for implementing CO<sub>2</sub> capture in European industries, enabling CCU and CCS to be a part of the emission reduction measures. CO<sub>2</sub> capture and purification technology development is necessary. The goal is to provide industries with a portfolio of technologies that can cater to the needs of any industry (varying in size, flue gas composition) and downstream CO<sub>2</sub> valorisation. Development of CCU and CCS 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.

#### A-6.a.1 Innovation objectives

Innovation objectives for flexible and modular capture technologies include the following:

- Reduce CO<sub>2</sub> capture CAPEX by more than 20% by 2030 and by 50% in 2050 compared to current technologies
- Reduce CO<sub>2</sub> capture energy consumption by more than 15% in 2030 and 25% in 2050 compared to current technologies
- Use more sustainable materials, (absorbents, adsorbents, membranes) by eliminating the waste by 2050 (e.g. by using materials that can be recycled)
- Use more cost-effective materials (absorbents, adsorbents, membranes) that are cheaper or more tolerant to contaminants
- demonstration of flexibility towards different gas compositions (CO<sub>2</sub> concentration and impurities).
- Demonstrate modularity (also units of 10ktCO<sub>2</sub> per year should be available at lower cost) and evaluate scalability

Innovation objectives for flexible and modular CO<sub>2</sub> purification technologies for higher concentrated sources:

- Develop purification technologies that can produce a CO<sub>2</sub> stream of the quality needed for different CO<sub>2</sub> valorisation pathways
- Develop purification technologies that can be integrated downstream of CO<sub>2</sub> capture and upstream of CO<sub>2</sub> valorisation

#### A-6.a.2 Impacts

For the assumptions and methodology underlying our impact estimations reference Appendix E .

##### **Greenhouse gas emissions**

This is presented under the carbon utilisation programmes.

##### **Waste**

Carbon capture enables carbon recycling in other applications. However, because CO<sub>2</sub> is a gaseous effluent it does not contribute towards the target of zero landfilling and water discharge.

About 3.2 kg of amine reclaimer waste is created per tCO<sub>2</sub> captured when using MEA (Flø, 2017). This waste can be used as a NO<sub>x</sub> reduction agent or can be combusted. Alternatively, it can also be treated (aerobic digestion). Adsorbents can be reused, and membranes can be burned or reused. As captured CO<sub>2</sub> volumes are currently low (i.e. mainly capture from concentrated sources for example for carbonated beverages), the waste impact is also

negligible. However, as carbon capture is used more in the future, this impact will become more relevant.

### **Competitiveness**

This innovation programme aims to decrease the costs of carbon capture. It will contribute to the increased competitiveness of carbon capture technologies and the CCU applications presented in other innovation programmes. Costs differ substantially for different technologies and we provide an indicative analysis. The CAPEX accounts for around one-third of the capture costs, solvents account for around 4%, and energy costs cover the rest (Flø, 2017). The energy savings in the technologies are key to achieve competitiveness. Combined, the innovation objectives for CAPEX and energy savings result in cost savings of 16% in 2030 and 32% in 2050. This assumes that solvent costs will not change.

**Table 17: Indicative carbon capture cost reductions**

Parameter	Share of capture costs (% of total)	Cost reduction 2030 (% of current)	Cost reduction 2050 (% of current)
<b>CAPEX</b>	33%	-20%	-50%
<b>Solvent costs</b>	4%	-	-
<b>Energy costs</b>	63%	-15%	-25%
<b>Total</b>	<b>100%</b>	<b>-16%</b>	<b>-32%</b>

### **A-6.a.3 Programming**

#### ***Flexible and modular capture technologies***

The CO<sub>2</sub> capture field is conducting a considerable amount of R&D. However, R&D is still needed for 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, considering upstream of the CO<sub>2</sub> capture point and downstream for CO<sub>2</sub> valorisation.
- Development of modular capture technologies (such an approach could contribute to reducing the risk and cost of CO<sub>2</sub> 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.
- Fundamentally new approaches to CO<sub>2</sub> capture.
- Highly efficient, long-lasting membranes that couple high permeability and selectivity.
- Solid adsorbents like zeolites, activated carbons, metal-organic frameworks, mixed metal oxides, and others (e.g. CaO) that capture more than 100 mg CO<sub>2</sub>/kg while being resilient to impurities in the gas streams.
- Develop fully integrated hybrid concepts, i.e. when combined, two CO<sub>2</sub> capture technologies show a significant added benefit towards energy and cost reduction

The circularity of materials used for CO<sub>2</sub> capture will be considered as well. This innovation programme aims to develop small, modular processes for capturing CO<sub>2</sub> at a competitive cost and an appropriate quality for various CO<sub>2</sub> valorisation routes.

#### ***Flexible and modular CO<sub>2</sub> purification technologies for higher concentrated sources***

CO<sub>2</sub> purification technology development is needed as an expansion to the need for CO<sub>2</sub> capture technology development. Two applications are expected. The first is the further purification of

already captured CO<sub>2</sub> and for the purpose of conforming to specifications of upstream CO<sub>2</sub> valorisation pathways, for flue gases with an already high CO<sub>2</sub> 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 Alternative hydrogen production routes in A-5.a). The CO<sub>2</sub>-concentration in the exit gas is lower than the concentration when amine technology is applied and will be in the range of 90% CO<sub>2</sub>. On top, the oxyfuel flue gas 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 SO<sub>x</sub>, NO<sub>x</sub>, HF, and HCl. It is similar to the raw gas input of an amine-capture unit but with less N<sub>2</sub>. The technology development required is to find a cost- and eco-effective way to eliminate minor components on top of the normal requirements of a capture and purification unit (CPU).

Effective CPUs must be developed as several downstream CCU-processes require a higher concentration and purity level. The optimal value chain for the various CCU-categories should be explored.

### ***Direct air capture***

The technologies above focus on point sources of CO<sub>2</sub> emissions. It is also possible to capture CO<sub>2</sub> 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 (DAC) offers the potential to build CCU value chains for short-lived applications with net zero GHG emissions (like capture of CO<sub>2</sub> from bio-origin), both of which are relevant for achieving climate neutrality. DAC could also be an option in cases where no CO<sub>2</sub> emission point sources or alternative carbon feedstocks are available. With CO<sub>2</sub> captured from the atmosphere high volumes of climate neutral materials (for example, GHG emission-free fuels for applications like aviation, where a high energy density is required) can be produced.

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

### **A-6.a.4 Investment needs**

The innovation programme includes the development of five generations of technologies until 2050:

1. For commercial CCU projects that are to be developed before 2024, two new carbon capture technologies are programmed at an estimated cost of €25 million each.
2. The next generation will be used in the roll out of other CCU technologies between 2024 and 2030. These five technologies will be demonstrated in 2020-2024.
3. The third generation will be applied commercially after 2030 and decrease costs further. To make this possible, pilot projects need to be funded in the period 2020-2024.
4. The fourth generation will follow based on newly developed technologies that are brought to TRL3 in 2020-2024.
5. Using the insights from the earlier generations, the development of direct air capture is started after 2024 and will be applied commercially in the late 2030s.

The following table shows the required investments for the portfolio of generations as they progress through the TRLs. DAC installations are expected to be more expensive as

concentrations of CO<sub>2</sub> are orders of magnitude lower. More effort is needed to capture and separate this CO<sub>2</sub>.

A non-technological project is programmed for the period 2024-2030 to work on any issues regarding the social acceptance of this technology.

**Table 18: Investment needs in € million<sup>81</sup>**

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Flexible and modular capture and purification technologies</b>	2020-2024	9x €3	4x €15	5x €25	2x €25		<b>€262</b>
	2024-2030		3x €15	2x €25	5x €25	€5	<b>€225</b>
	2030-2040			2x €25	2x €25		<b>€150</b>
	2040-2050						<b>€0</b>
<b>Direct air capture</b>	2020-2024						<b>€0</b>
	2024-2030	15x €3					<b>€45</b>
	2030-2040		5x €15	2x €25			<b>€125</b>
	2040-2050				2x €50		<b>€100</b>
<b>Total</b>		<b>€72</b>	<b>€180</b>	<b>€275</b>	<b>€375</b>	<b>€5</b>	<b>€907</b>

#### **A-6.a.5 Success factors**

- Demand for CO<sub>2</sub> as feedstock is key and will trigger the demand for capture (linked to the subsequent innovation programmes).
- Increasing the CO<sub>2</sub> concentration of industrial flue and processes gases through process intensification. The increased concentration enables lower capture and purification costs both in CAPEX and OPEX. This will simultaneously reduce the total volume of flue gas, which is an added benefit. Lower levels of impurities will also enable lower costs. In the innovation programme, Breakthrough efficiency improvement (A-9.b), technologies are developed to achieve this.
- Policies must provide incentives for CO<sub>2</sub> capture and utilisation to improve the business case beyond what the innovation programs outlined here can deliver (in the next decade).

<sup>81</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-7 CO<sub>2</sub> and CO utilisation in minerals

### A-7.a CO<sub>2</sub> utilisation in concrete production

Fresh concrete for pre-cast elements can be cured in a CO<sub>2</sub> environment. During this curing process, CO<sub>2</sub> enters the fresh concrete and reacts with the Ca(OH)<sub>2</sub> present in the poured concrete to create CaCO<sub>3</sub>, sequestering CO<sub>2</sub> into the concrete matrix. The strength development is also enhanced, so in order to reach the same performance of concrete the kilograms of cement per cubic metre of concrete can be reduced, reducing the overall CO<sub>2</sub> footprint of the cubic metre concrete at given strength.

This process only applies to pre-cast concrete because a curing chamber is needed as it takes time before the CO<sub>2</sub> fully reacts. Moisture and temperature levels should be managed. Up to 20% of all cement is in pre-cast and this share is increasing.

Companies have already developed this technology for a special type of cement (wollastonite), reaching TRL9. However, it is not used much because special cement is needed, and it is difficult to convert kilns. Applying this same technological concept to regular cements requires further deployment, as it is currently around TRL5. If successfully deployed, this will make possible the more general application of the technology to cure fresh pre-cast concrete with CO<sub>2</sub>. Mandatory to this deployment are investigations and tests for porosity, optimal recipes for fresh concrete, and equipment to make low capital-intensive curing chambers available.

This technology is different from concrete curing, which adds several kilograms of liquid CO<sub>2</sub> into ready mix concrete when it is poured, where the CO<sub>2</sub> acts as an accelerator/agitator for the hardening process. In concrete curing, it does not bind to all the calcium hydroxide in the mix and only relatively small volumes of CO<sub>2</sub> are used.

#### A-7.a.1 Innovation objectives

- Development of regular pre-cast CO<sub>2</sub>-curing (other than wollastonite) from TRL5 to TRL9
- Development of special reinforced precast CO<sub>2</sub>-curing from TRL2 to TRL9

#### A-7.a.2 Impacts

For the assumptions and methodology underlying our impact estimations reference Appendix E .

##### **Greenhouse gas emissions**

Wollastonite reduces CO<sub>2</sub> by up to 70% compared to conventional concrete (Solidia, 2020). As it only applies to pre-cast applications, which total about 20%, the potential reduction is equal to 12% of cement emissions. With total emissions of 102 MtCO<sub>2</sub> in the cement sector, the reduction potential of this technology is 12.2 MtCO<sub>2</sub>.

None of the technologies will be at TRL9 in 2024 and the 2030 impact is only from the TRL9 projects that are delivered before 2030. It is assumed that the four installations for regular pre-cast CO<sub>2</sub> curing collectively reduce about 0.5MtCO<sub>2</sub>.

##### **Waste**

Carbon capture enables recycling carbon in other applications. However, because CO<sub>2</sub> is a gaseous effluent it does not contribute towards the target of near 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 the use of less material.

### A-7.a.3 Programming

#### Regular pre-cast applications

- The TRL maturation of this application by demonstration plants using standard Portland cement and delivering CO<sub>2</sub>-cured precast products to the market, first with eight TRL4-6 projects to test concepts (€3 million each), then four TRL7-8 projects (€10 million each), and finally TRL9 demonstration in four applications (€12 million each).
- Developing pre-cast concrete customers' understanding that low carbon pre-cast products are being developed and should be marketed as such, and investigating standardisation and procurement issues and business models in a CSA of €5 million.
- Rapid deployment of CO<sub>2</sub>-curing in the precast concrete market through a combination of commercial benefits, stimulating regulations (low carbon concrete products), and know-how support to precast producers.

#### Special reinforced pre-cast applications

- Widening the application-range of CO<sub>2</sub>-curing by R&D into stainless steel reinforcement or carbon fibres reinforcement for pre-cast reinforced elements, which with normal iron reinforcement bars are not suitable for CO<sub>2</sub>-curing.
- Starting with TRL1-3 projects, 15 projects are estimated to be needed to explore different options (€1.5 million each).
- Eight TRL4-6 projects (the most promising technologies) starting in 2024 of €3 million each, then four TRL7-8 projects (€10 million each), and TRL9 demonstration in four applications (€12 million each).

### A-7.a.4 Investment needs

Table 19: Investment needs in € million<sup>82</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Regular pre-cast CO <sub>2</sub> -curing	2020-2024		8x €3			€5	€29
	2024-2030			4x €10	4x €12		€88
	2030-2040						€0
	2040-2050						€0
Special reinforced pre-cast CO <sub>2</sub> -curing	2020-2024	15x €1.5					€22.5
	2024-2030		8x €3				€24
	2030-2040			4x €10	4x €12	€5	€93
	2040-2050						€0
<b>Total</b>		<b>€22.5</b>	<b>€48</b>	<b>€80</b>	<b>€96</b>	<b>€5</b>	<b>€256.5</b>

### A-7.a.5 Success factors

- Develop pre-cast concrete customers' understanding that low carbon pre-cast products are being developed and should be marketed as such.
- Rapidly deploy CO<sub>2</sub>-curing in the precast concrete market by combining of commercial benefits, stimulating regulations (low carbon concrete products) and know-how support to precast producers.

<sup>82</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-7.b CO<sub>2</sub> and CO mineralisation to produce building materials

This innovation programme covers several applications for mineralisation of CO<sub>2</sub> and CO in building materials. The most promising applications are concrete recycling and natural materials mineralisation.

### Mineralisation of recycled concrete

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

The 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 fine parts are treated (milling/separation) to get the cement-paste as a fine particle back, the Ca(OH)<sub>2</sub> in this material will react easily with CO<sub>2</sub> to form CaCO<sub>3</sub> particles that make 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 and 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 developments. The focus should be on capture efficiency, handling fines, and the long-term availability of scrubber areas where the CO<sub>2</sub> is captured, among others.

CaO or MgO rich materials that are by-products or recycled materials (such as steel-slag and recycled concrete fines) are generally more reactive than natural materials, thus requiring less energy to execute the re-carbonation. As end-of-life concrete is to a large extent landfilled and recycled concrete is largely 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 in a large CO<sub>2</sub> sequestration and into valuable (building) materials.

### Mineralisation of natural materials

Natural minerals like olivine, serpentine, and basalt have the potential to sequester CO<sub>2</sub> due to the 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<sub>2</sub> to the carbonatable fractions is limited. By mining those minerals, increasing surface area, and lifting temperature and pressure, the process of mineralisation can be accelerated so full potential is exploited within a reaction time of 1 hour. Compared to using recycled products, no purification is needed.

#### Text box 7: Natural minerals mineralisation in aluminium production

The recently launched AISiCal project (IFE, 2019) is an example of how mineralisation of natural materials can be integrated in the process industries. This project develops a new technology for making alumina out of aluminium-rich mineral that also contains calcium: anorthosite. CO<sub>2</sub> is mineralised to the calcium in the mineral, creating the by-product CaCO<sub>3</sub>. This by-product can be used in the cement industry. At the same time, the calcium is taken out of the mineral. The process also removes the silica from the mineral and leaves the alumina. The development of the pilot plant in Norway is funded by Horizon 2020.

Technology development is especially needed for energy efficiency, as minerals require crushing or milling as well as increased temperature and pressure to accelerate the mineralisation

process. The separation of final products and the determination of the final products' maximum market value needs further investigation.

Finally, the logistics related to making minerals available near the CO<sub>2</sub> source needs further investigations and demonstrations. Research is being conducted in the sector on how much cement can be displaced by these materials and what the full value chain impact and business model could look like.

### **SPIRE project this programme builds on**

**RECO2DE** develops a 20% reduction of CO<sub>2</sub> emissions in the cement industry by CO<sub>2</sub> capture, purification, and conversion by the generation of nano-fillers (CaCO<sub>3</sub>) through the electrocatalytic reduction of CO<sub>2</sub> to added-value products. It can be clustered with OCEAN.

#### **A-7.b.1 Innovation objectives**

- Recycled concrete:
  - o Produce composite cement containing >20% in mass of re-carbonated RCF in 2030 and 30%-40% in 2050
  - o Develop re-carbonation of RCF from TRL3 to TRL9 in 2030
  - o Develop high substitution composite cements from TRL2 to TRL9
  - o Develop integrated CO<sub>2</sub>-capture and valorisation from TRL3 to TRL9
- Natural minerals:
  - o Develop natural minerals carbonation from TRL3 to TRL9 by 2035
  - o Assess the mitigation potential of the full value chain and decide whether to continue

#### **A-7.b.2 Impacts**

For the assumptions and methodology underlying our impact estimations reference Appendix E .

##### ***Greenhouse gas emissions***

According to a recent study, the re-carbonation of **recycled concrete** can sequester 0.1 tCO<sub>2</sub> per tonne of waste concrete (Pasquier, Kemache, Mocellin, Blais, & Mercier, 2018). Assuming about 50 million tonne waste concrete is generated in Europe annually,<sup>83</sup> this implies a potential impact of 5 MtCO<sub>2</sub>. Additionally, new cement is displaced, resulting in additional CO<sub>2</sub> emission reductions. If there are 20% losses, the 50 Mt concrete waste can displace 40 Mt of primary concrete. Assuming emissions of around 0.1 tCO<sub>2</sub>/tonne primary concrete,<sup>84</sup> this amounts to 4 MtCO<sub>2</sub>.

In 2030, four TRL9 installations will be established that are estimated to cover about 1% of the potential and therefore have an emission reduction impact of 0.13 MtCO<sub>2</sub> in 2030.

It is not certain where carbonated natural minerals displace other materials, but a reasonable proxy could be the market size of fly ashes in cement production (as experts expect that the applications will be similar). About 34 Mt of fly ash were produced in Europe in 2013, most of which is used by the construction industries (European Climate Foundation, 2018). In extreme cases, this volume would be fully substituted (as coal phases out in the future), and assuming the need of 2.5 tonnes rock per tonne CO<sub>2</sub>, 34 Mt of carbonated mineral is equivalent to 13 MtCO<sub>2</sub>. No GHG impact is expected in 2030.

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

<sup>83</sup> There are no statistics on concrete waste in Europe, and therefore here we take a conservative estimation. This estimate suggests that concrete amounts to about 15% of total construction and demolition waste (i.e. 345 Mt; see Appendix E for details), which seems conservative when comparing to a study by (Deloitte, 2017).

<sup>84</sup> Assuming density of concrete of 2.4 t/m<sup>3</sup> and 0.25 tCO<sub>2</sub>/m<sup>3</sup> concrete

## **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<sub>2</sub> is a gaseous effluent it does not contribute towards the target of near zero landfilling and water discharge.

## **Competitiveness**

The re-carbonated recycled concrete is about as good as fly ash. The current value of fly ash ranges from one-third to two-thirds of cement's value. A landfill ban on this material would create incentives and the carbon price (if this will incentivise CCU in the future).

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

### **A-7.b.3 Programming**

Development towards 2030

- Recycled concrete
  - Develop the TRL of this application by demonstration plants where the energy efficiency of the recycled concrete fines separation will be optimised, and the logistical concept for reclaiming materials and making CO<sub>2</sub> available for the reaction are further developed.
  - Develop 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.
  - Design 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.
  - Eight projects for TRL4-6 of €3 million each before 2024.
  - Four projects for TRL7-8 of €10 million each between 2024-2030.
  - Two projects for TRL9 of €25 million each between 2024-2030.
- Natural materials
  - Develop the technology's TRL where the energy balance is to be found between the amount of CO<sub>2</sub> per tonne of mineral and the energy needed to achieve it.
  - Develop 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<sub>2</sub> source, and the market for the final products generated.
  - Three projects for TRL4-6 of €3 million each before 2024.
  - Four projects for TRL7-8 of €8 million each between 2024-2030.
  - Two projects for TRL9 of €12 million each between 2024-2030.

Development towards 2050:

- Recycled concrete
  - Refine the technology to exploit the maximal potential of end-of-life concrete in terms of CO<sub>2</sub> sequestration.
  - Develop the technology to increase its applicability.
  - Two TRL9 projects of €25 million each.
- Natural materials
  - Implement the most ecological and economical applications.
  - Develop the technology to increase its applicability.
  - Two TRL9 projects of €12 million each.

#### A-7.b.4 Investment needs

Investments are relatively low because of the relatively small installation size.

Table 20: Investment needs in € million<sup>85</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Recycled concrete</b>	2020-2024		8x €3				€24
	2024-2030			4x €10	2x €25		€90
	2030-2040				2x €25		€50
	2040-2050						€0
<b>Natural materials</b>	2020-2024		3x €3				€9
	2024-2030			4x €8	2x €12		€56
	2030-2040				2x €12		€24
	2040-2050					€4	€4
<b>Total</b>		€0	€33	€72	€148	€4	€257

#### A-7.b.5 Success factors

- Realise regulatory measures that avoid concrete being landfilled and avoid recycling only for coarse material recovery, instead 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 or concrete with a certain share of re-carbonated RCF.
- Rapid deployment of business of RCF re-carbonation, using optimal logistical concepts for each application.
- End of waste status can be hard to obtain, and this can be a barrier for recycling and for cross-border transport of used materials. This barrier must be removed for this innovation programme to achieve full potential.
- Policies on waste and GHG are necessary to provide incentives for users to switch from their current materials to carbonated minerals.
- Access to raw materials.

<sup>85</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-8 CO<sub>2</sub> and CO utilisation in chemicals and fuels

Several target molecules can be used as chemicals or as energy carriers, and the related technology developments needed will be the same while the non-technical issues and related impact will be different. Technology developments for chemical and energy carriers will be conducted under the same innovation programme, and distinctions regarding applications will be made by the objective levels in each innovation programme. The figure below shows what routes are available.

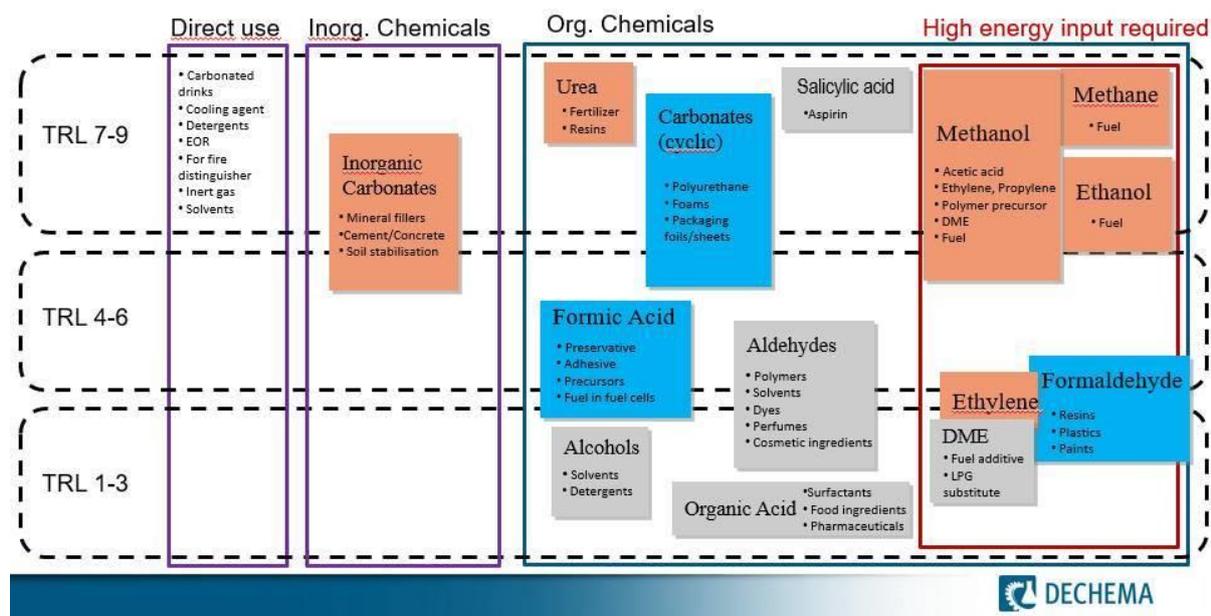


Figure 6: Target molecules of chemical CO<sub>2</sub> utilisation routes and status of development (DECHEMA, 2017)

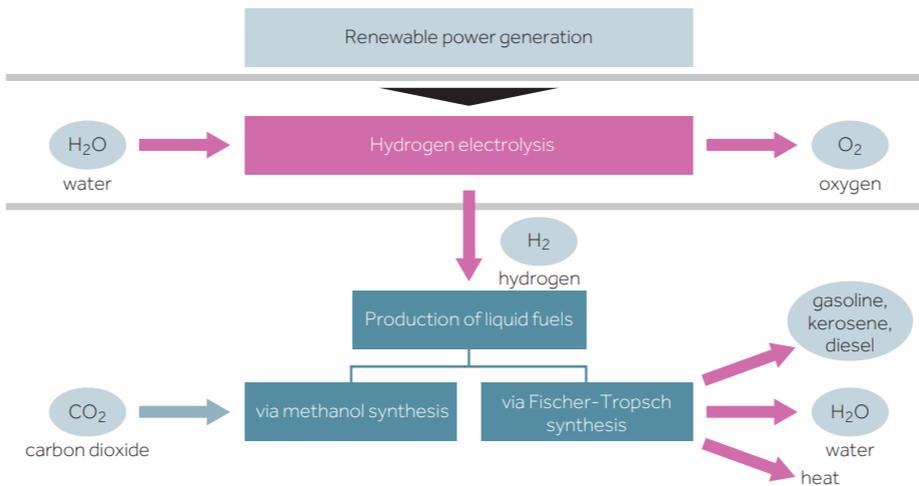
### Overview e-fuels technical routes

E-fuels production routes consist of e-hydrogen reacting with captured CO<sub>2</sub>, followed by different conversion routes according to the final e-fuel (such as the methanisation route for e-methane; methanol synthesis for e-methanol, e-DME, e-OME or e-liquid hydrocarbons; or the reverse water-gas shift (RWGS) reaction to produce syngas + Fischer-Tropsch synthesis to produce e-liquid hydrocarbons, such as e-gasoline, e-diesel or e-jet. Different routes could be envisaged, summarised in the chart below:

E.g. Scheme for production routes below

Figure 1: E-liquids production routes

Source: Frontier Economics (2018)



According to the EC’s Long-Term Strategy, CCU is expected to play a major role in 2050. Figure 7 depicts the volume of CO<sub>2</sub> captured to produce synthetic fuels (EC, 2018). Additionally, CCU can be used to produce carbon-based chemicals.

In this innovation area, four innovation programmes are distinguished. The first three focus on use of CO<sub>2</sub>. Two of the three aim for CO<sub>2</sub>’s use to build chemical building blocks (photocatalytic and other catalytic technologies), the third aims for the direct use of CO<sub>2</sub> in polymers. The fourth focuses on CO from industrial processes.

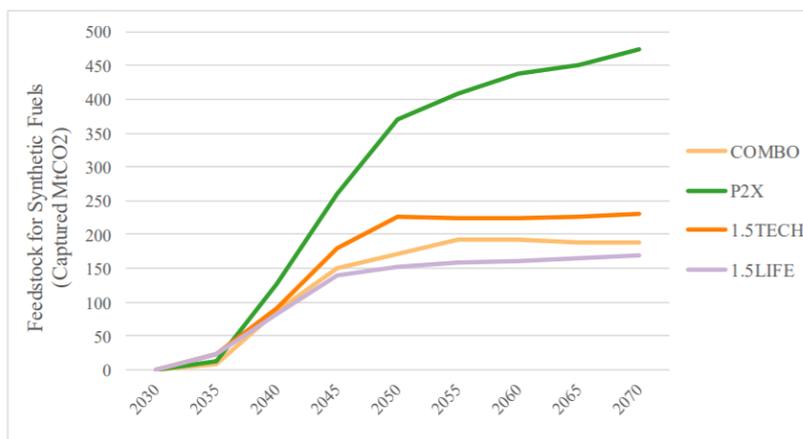


Figure 7: Expected CCU for fuels according to EC scenarios (EC, 2018)

### A-8.a Artificial photosynthesis

This programme focuses on the development of disruptive technologies that allow the production of chemicals and fuels based on CO<sub>2</sub>, water, and energy from sunlight.

For the chemical CO<sub>2</sub> valorisation through direct utilisation of sunlight, advanced integrated photo(electro)catalytic systems have to be developed for the conversion of CO<sub>2</sub> to C<sub>1</sub> molecules and the conversion of CO<sub>2</sub> to C<sub>n+1</sub> molecules. This process enables the increase in efficiency, selectivity, and stability, and a decrease to the cost of technologies. This allows energy carriers and intermediates for high added value chemicals to be selectively produced in sustainable photocatalytic processes.

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, Digital materials design, in A-13.a), 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.
- Develop low energy intensive concentration systems for CO<sub>2</sub> derived liquid materials to reach the required product concentration levels.
- Advanced materials and high performance catalysts that will reduce energy requirements for CO<sub>2</sub> reduction and water splitting in an economic and sustainable way.

### **A-8.a.1 Innovation objectives**

The objectives are to:

- Produce chemicals through CO<sub>2</sub> to C<sub>1</sub> and CO<sub>2</sub> to C<sub>n+1</sub> conversions with low carbon footprint independent of the availability of renewable electricity.
- Production of fuels C<sub>n+1</sub> molecules with a 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.

### **A-8.a.2 Impacts**

For the assumptions and methodology underlying our impact estimations reference Appendix E .

#### ***Greenhouse gas emissions***

As technically the photocatalytic processes can be applied to produce many different chemicals and fuels, their potential is similar to that of the innovation programme Catalytic conversion of CO<sub>2</sub> to chemicals/fuels (A-8.b). The estimated impact is the same as derived from DECHEMA in that innovation programme: 134 MtCO<sub>2</sub> reductions for chemicals, and 207 MtCO<sub>2</sub> reductions for fuels (DECHEMA, 2017). See Appendix A-8.b for more details about the impact estimation.

No GHG impact is expected in 2030 as no TRL9 FOAK is expected before 2030.

#### ***Waste***

The chemical valorisation of CO<sub>2</sub> can contribute to the development of a more circular economy. However, because CO<sub>2</sub> is a gaseous effluent it does not directly contribute towards the target of near zero landfilling and water discharge.

#### ***Competitiveness***

The costs of direct production of fuels or chemicals from sunlight are CAPEX driven because they do not require additional energy input. However, because the technologies are still immature, it is not yet 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 1 m<sup>2</sup>. Assuming an efficiency of 20% and a capacity factor of 30%, this 1 m<sup>2</sup> system will generate 526 kWh of fuel each year (i.e. 1,892 GJ). Assuming a kerosene price of €0.75/litre and gross calorific value of 37.1 MJ/litre, that amounts to total revenue of €38/year for this 1 m<sup>2</sup> system. At a 10% discount rate and 25-year lifetime, the capital recovery factor is 11%. The annuitised CAPEX would be €38/year at a CAPEX of €347/m<sup>2</sup>. Assuming that this CAPEX is the only cost factor, this means that (under these illustrative assumptions) artificial photosynthesis would be competitive with kerosene at a CAPEX of €347/m<sup>2</sup>.

### **A-8.a.3 Programming**

#### ***First generation***

- Some technologies are already at TRL3. Competitive systems need to be developed for these technologies to convert sunlight, H<sub>2</sub>O, and CO<sub>2</sub> into valuable materials. Innovation is needed to enable intensification of solar to chemical energy process.
- The projects already at TRL3 will be developed further. For this, 16 TRL4-6 projects are expected in 2020-2024 for different technologies and target molecules (€8 million per project).
- Two TRL7-8 projects are programmed from 2024-2030, as likely several technologies are outcompeted by the prospects of the second-generation technologies. The projects are estimated to require €20 million each.
- Two TRL9 demonstration projects of €160 million each are programmed for 2030-2040.

### Second generation

- Many new PEC technologies will be developed to find new and more efficient applications. Therefore, 30 TRL1-3 projects are programmed in 2020-2024 of €2.5 million each.
- The projects that are promising at TRL3 will be developed further. For this, 12 TRL4-6 projects are foreseen in 2024-2030 for different technologies and target molecules (€8 million per project).
- Six TRL7-8 projects are programmed in 2030-2040 for the most promising second-generation technologies. The projects are estimated to require €20 million each.
- Two TRL9 demonstration projects of €160 million each are programmed for 2040-2050.

### A-8.a.4 Investment needs

Table 21: Investment needs in € million<sup>86</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Artificial photo-synthesis	2020-2024	30x €2.5	16x €8				€203
	2024-2030		12x €8	2x €20			€136
	2030-2040			6x €20	2x €160		€440
	2040-2050				2x €160		€320
<b>Total</b>		<b>€75</b>	<b>€224</b>	<b>€160</b>	<b>€640</b>	<b>€0</b>	<b>€1,099</b>

### A-8.a.5 Success factors

- Complementary innovations are needed that address the intermittency of the energy source (reference the innovation programme Flexibility and demand response, in A-1.d)
- Appropriate evaluation of the environmental impact, especially GHG impact.
- Supporting policy frameworks that recognise CO<sub>2</sub> emission avoidance in the EU ETS.
- Support measures for production of chemicals from CO<sub>2</sub> that effectively contribute to carbon circularity.
- Standards and labels that demonstrate sustainability benefits to support market uptake.

### A-8.b Catalytic conversion of CO<sub>2</sub> to chemicals/fuels

This innovation programme excludes photocatalytic conversion of CO<sub>2</sub>, as this is included in the innovation programme on artificial photosynthesis.

#### SPIRE projects this programme builds on

**FRESME** developed the conversion of CO<sub>2</sub> and H<sub>2</sub> from blast furnace gases into methanol at TRL6-7 with potential to go to TRL9 by 2025 via demo projects in five different plants. Cost reductions of 80% are expected and up to 66 MtCO<sub>2</sub> emissions can be avoided. The technology can be taken to TRL9 by 2025 with an additional €4-€20 million (R&D budget only).

<sup>86</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

**ICO2CHEM** has an upscaled reactor to convert CO<sub>2</sub> into waxes (via an innovative Fischer-Tropsch) and the further conversion into non-fossil-based coatings. Upscaling can start from 2021 on to TRL9.

**CO2-EXIDE** is coupling two electrochemical reactions to produce ethene and hydrogen peroxide, and thereafter ethylene oxide, from biogas-derived CO<sub>2</sub>. Currently at TRL4, a TRL5-6 demo is expected by 2021 and a TRL9 facility by 2030. Use of 10% of the CO<sub>2</sub> from biogas will give a 2.3 MtCO<sub>2</sub>/yr reduction in GHG emissions. A competitive process is expected at a green electricity price of <€40/MWh.

**OCEAN** provides an electrochemical conversion of CO<sub>2</sub> into ethylene glycol with a final potential in CO<sub>2</sub> reduction of 2.8 MtCO<sub>2</sub> and will be at TRL5 in 2021. It can further be developed to TRL9 by 2030. It can be clustered in the CCU-projects and especially with RECO2DE.

**CO2MOS** will combine the hydrogenation of CO<sub>2</sub> to methanol and the conversion of methanol to C<sub>3</sub> hydrocarbons in the same reactor, to overcome the low equilibrium yields for CO<sub>2</sub> hydrogenation. Through the substitution of CO<sub>2</sub> for carbon from fossil fuels, the TRL9 technology (which is first expected to be available in 2030) will decrease GHG emissions by 0.8 MtCO<sub>2</sub>/yr, increasing to 4 MtCO<sub>2</sub>/yr by 2034. Competitiveness will be enhanced by increasing the availability of propane in LPG.

**eCOCO2** is developing a modular, TRL5 electrochemical reactor to produce >250 g jet fuel per day from CO<sub>2</sub> and H<sub>2</sub>O. Additional investment is anticipated to reach TRL9. GHG reductions of 1.8 MtCO<sub>2</sub> are estimated from the production of jet and industrial fuel

**MEFCO2** will produce methanol from the CO<sub>2</sub> in industrial flue gas streams. The technology is modular and for intermediate scale plants so that it can be readily adapted to a variety of plant sizes and gas compositions. A 68% reduction in GHG emissions will be available with the TRL9 technology in 2025 with extra support. It can be clustered with FRESME.

### A-8.b.1 Innovation objectives

The objectives are to:

- Develop framework to compare different routes and applications.
- Produce chemicals/fuels through CO<sub>2</sub> to C<sub>1</sub> molecules and CO<sub>2</sub> to C<sub>n+1</sub> molecules with lower environmental footprints compared to the current production route. This includes net CO<sub>2</sub> emission reduction evaluated with appropriate system boundaries and methodology.
- Production of C<sub>n+1</sub> molecules with low carbon footprints for chemical and energy carrier applications.
- Contribution to renewable electricity storage in chemical energy carriers through the conversion of CO<sub>2</sub> through Power-to-X technologies.

## A-8.b.2 Impacts

For the assumptions and methodology underlying our impact estimations reference Appendix E .

### **Greenhouse gas emissions**

The processes in this innovation programme can be applied to produce many chemicals and fuels. The GHG emissions reduction impact is derived from a DECHEMA study that covers the main chemical routes. In its maximum scenario, this study reports GHG savings in the chemicals sector of 186 MtCO<sub>2</sub> in 2050 (DECHEMA, 2017). However, using this 2050 number is inconsistent with the other impact estimations, as the study assumes sector growth of 1%/year, summing up to 39% growth in 2050 compared to 2017. To account for this growth, the reduction potential compared to today's emissions is 134 MtCO<sub>2</sub>. This scenario-based estimation approach differs from other estimations and is not directly comparable with the other impact estimations in this roadmap.

Additionally, the production of synthetic fuels can achieve emission reductions outside of the P4Planet sectors. DECHEMA estimated the potential savings at 287.5 MtCO<sub>2</sub> in 2050. Converted to 2017, this amounts to 207 MtCO<sub>2</sub>. In the EC long-term strategy, the potential for CCU for production of synthetic fuel is estimated at 150 MtCO<sub>2</sub> and 225 MtCO<sub>2</sub> in 2050 in the 1.5LIFE and 1.5TECH scenarios, respectively (EC, 2018).

The impact is smaller in 2030, as two TRL9 plants are running in that year. As it is still uncertain which projects that will be, we estimate the combined impact to be in the range of 1 MtCO<sub>2</sub>.

### **Waste**

The chemical valorisation of CO<sub>2</sub> can effectively contribute to the development of a more circular economy. However, because CO<sub>2</sub> is a gaseous effluent it does not contribute towards the target of near zero landfilling and water discharge.

### **Competitiveness**

As for the estimation of the GHG impact, the competitiveness of CCU options is difficult to estimate. The existing assessment from Dechema for Methanol from CO<sub>2</sub> based on existing technologies is shown here. For other target molecules the results will differ. A generic rule is that the more original CO<sub>2</sub> molecule remains, the more attractive the route. However, due to the many technological options and low maturity, it is extremely difficult to estimate costs towards post-2030.

#### *Methanol*

DECHEMA analyzed the costs of producing methanol in a catalytic conversion of CO<sub>2</sub> (DECHEMA, 2017). Methanol produced from fossil feedstock costs around 400 €/tonne. According to this study, renewable electricity should be available at prices below €22/MWh (i.e. €6/GJ) at 7,000 h/year or €16/MWh (i.e. €4.5/GJ) at 5,000 h/year. This analysis does not take technological development into consideration, and therefore technological improvements costs can be reduced and the technology might be competitive in 2050 at higher electricity prices. DECHEMA used different underlying assumptions than used in this roadmap and as a result this analysis is inconsistent with the analyses conducted for other innovation programmes.

When using the methanol as a fuel, DECHEMA found that it would be competitive with bioethanol production costs (they estimate bioethanol production costs at €1.5/GJ to €2.5/GJ), but it is a factor 2 above conventional gasoline production (DECHEMA, 2017).

In some cases, waste hydrogen or hydrocarbons are locally available, in those cases CCU routes would be competitive sooner.

A literature review produced by Concawe ([https://www.concawe.eu/wp-content/uploads/Rpt\\_19-14.pdf](https://www.concawe.eu/wp-content/uploads/Rpt_19-14.pdf)) explores the potential primary uses of a wider range of CCU-synthetic fuels across

different transport segments including a qualitative overview of lower heating value, storability, infrastructure and powertrain development. As a summary, when these synthetic fuels are considered (CCU), the potential to abate CO<sub>2</sub> emissions could vary between 85 and ~95% (Well-To-Tank –WTT- basis) when compared with current fossil alternatives. This low GHG intensity together with their compatibility with existing vehicles, equipment and infrastructure makes these type of fuels a compelling alternative to reduce GHG emissions in the use phase. Regarding their production cost, they are currently relatively high (up to 7 euros/litre) but expected to decrease over time due to economies of scale, learning effects and an anticipated reduction in the renewable electricity price. Different sources claim that all these improvements could lead to a cost of 1–3 euros/litre (without taxes) in 2050.

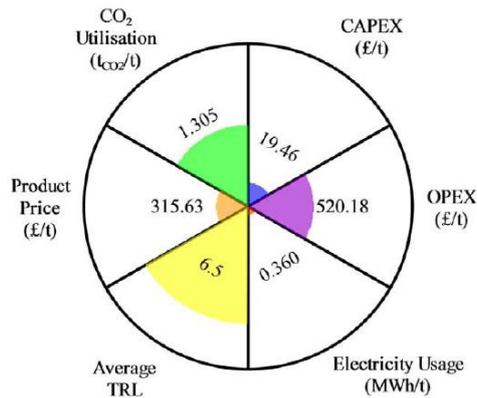
### **A-8.b.3 Programming**

Technologies currently scaling to TRL5-7 (e.g. electrochemical based reduction, Fischer-Tropsch starting from CO<sub>2</sub> rich streams and renewable hydrogen, (thermal) dry reforming, catalytic chemical looping) should evolve to TRL7-8 by 2030. This can include reactor designs (e.g. low temperature aqueous based reactors, or high temperature co-electrolysis), unit operations such as integration with separation processes, flexible energy grid use, process design and operability, process scale-up, and improvement of previously identified catalytic systems with respect to stability (lifetime) and selectivity.

New technologies or technologies with hurdles to catalyst development (yield, selectivity, stability), reactor designs, unit operations such as integration with separation processes, flexible energy grid use, and process design and operability at TRL below 5 but with a potential of surpassing the current TRL5-9 technologies, should increase at least 1 TRL scale by 2030. This includes barriers such as the use of electrocatalysis for specific target molecules at higher yields, plasma-based processes towards syngas or CO, plasma catalytic processes to C<sub>2</sub>-C<sub>n+1</sub> components, ionic liquid-based technologies, bio or electrocatalysis, or other new technologies. High temperature electrolysis (solid oxide electrolysis) as a method to produce hydrogen is under research and is especially interesting for industrial applications as a potential technology to efficiently produce syngas or even pure CO using CO<sub>2</sub> as feedstock.

Integrated processes include sorption enhanced processes or integrated separation. Different TRLs can be expected depending on the TRL of the individual technological components and their integration challenges. Their integration should obtain benefits with respect to environmental, sustainability, safety or techno-economic aspects. A selection framework will be developed for this purpose.

The innovation programme will need to determine which technologies are most promising, especially for lower TRL technologies. This portfolio approach will continue towards 2040 to continuously identify and develop opportunities for more efficient technologies. Since there are many ways to prioritise technologies, a multi-criteria approach is recommended for the selection of projects, such as in the figure below (Jarvis & Samsatli, 2018). A key indicator is the total avoidance of CO<sub>2</sub> emissions.



**Figure 8: 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 that enable understanding how to evaluate the environmental impact of CO<sub>2</sub> valorisation technologies for various applications. No global standards exist for the life cycle assessment or TEA for CO<sub>2</sub> valorisation. Guidelines have been developed by RWTH Aachen, TU Berlin, University of Sheffield, and IASS Potsdam, but further developments are needed according to the authors (Zimmermann, et al., 2020). Education and social acceptance are also key to the successful implementation of these technologies.

Technology developments are needed to:

- Improve the economics of the conversion of CO<sub>2</sub> to C<sub>1</sub> molecules
- Move conversion of CO<sub>2</sub> to C<sub>n+1</sub> in (mostly one step) reactions to TRL3 before 2025, TRL5 by 2035, TRL7 before 2035, and TRL9 by 2040.
- Linking different technologies to create process integration and intensification as they are expected to enhance impact. TRL4-6 before 2030, TRL9 by 2040/2050.
- Where the catalyst is still an issue, lower TRL activities are required with TRL9 as objective for 2040/2050.

Technology priorities include:

- The utilisation of less purified or diluted streams of CO<sub>2</sub> with the purpose of minimising the cost of the purification phase or with the purpose of using poison resistant catalysts.
- Robust CO<sub>2</sub> conversion process with high productivity.
- Development of highly active and selective catalysts with sufficient lifetime, for more efficient processes (see innovation programme, A-9.a Next-gen catalysis).
- Processes at lower temperature or pressure.
- Integrated processes where separation, (waste/recovery) heat, or sorption are integrated with the conversion process with the intention to intensify its performance.
- Integrated processes where mixtures of CO and CO<sub>2</sub> can be used without or with limited separation.
- Process design linking unit operations including electric grid integration.
- Catalytic processes for the transformation of CO<sub>2</sub> into CO.

#### **A-8.b.4 Investment needs**

A broad portfolio of technology options should be explored to cover the various production routes from CO<sub>2</sub> to various C<sub>1</sub> and C<sub>n+1</sub> molecules.

The first wave of technologies are already in the pipeline. The second wave should be created in 2020-2030 (low-TRL). In 2030-2040, new low TRL technologies are developed to make improvements, which is necessary to find breakthrough technologies. Technologies should show

that they have more potential than those in higher TRLs. The investments for TRL9 projects range between €25 million and €150 million. In the estimations below, €100 million is chosen as a typical number.

**Table 22: Investment needs in € million<sup>87</sup>**

Activity	Timing	TRL 1-3	4-6	7-8	9	Non-technological	Total
<b>Catalytic conversion of CO<sub>2</sub> to chemicals or fuels</b>	2020-2024	15x €3	8x €10			€3	<b>€128</b>
	2024-2030	15x €3	8x €10	8x €20	2x €100		<b>€485</b>
	2030-2040	15x €3	10x €10	10x €20	5x €100	€5	<b>€850</b>
	2040-2050			3x €20	8x €100		<b>€860</b>
<b>Total</b>		<b>€135</b>	<b>€260</b>	<b>€420</b>	<b>€1,500</b>	<b>€8</b>	<b>€2,323</b>

### A-8.b.5 Success factors

- Standardise multi-criteria analysis to evaluate the impact of technologies for various applications.
- Appropriate cost-effective CO<sub>2</sub> capture and purification technologies (see innovation programme, A-6.a Flexible CO<sub>2</sub> capture and purification technologies).
- Access to climate neutral hydrogen, electricity, or waste/by-products at competitive prices (depending on the technology).
- Evaluate the environmental impact, especially of GHG (including industrial symbiosis, waste heat).
- Base policy framework on the applications (chemical, transport, energy storage), including appropriate recognition of CO<sub>2</sub> emission avoidance in EU ETS where relevant.
- Support measures to produce chemicals/fuels from CO<sub>2</sub> that effectively contribute to carbon circularity.
- Create standards and labels that demonstrate sustainability benefits to support market uptake.
- Encourage education and social acceptance.

<sup>87</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-8.c Utilisation of CO<sub>2</sub> and CO as a building block in polymers

CO<sub>2</sub> can be used as an alternative carbon resource to produce polymers through two major chemical routes by the direct use of CO<sub>2</sub> as a polymer building block or the indirect use of intermediates that are obtained by chemical transformation of CO<sub>2</sub>. Several CO<sub>2</sub> to polymer technologies have been successfully demonstrated at lab and pilot scale, and a first demo plant built in Europe.

The innovation programme focuses on the direct production of polymers from CO<sub>2</sub>. By 2030 it aims for at least one large-scale commercial plant based on developed technologies and the development of polymers from CO<sub>2</sub> for new applications (differentiated and competitive). By 2050 it aims to scale up these new applications to industrial scale.

### **SPIRE project this programme builds on**

**CARBON4PUR** allows the conversion of CO to polyols at a TRL5-6 in 2021 with potential to move to TRL7 in 2023 with extra budget. It allows to make new polyols suitable for other applications. The impacts on GHG emission and waste reduction and competitiveness will be provided in September 2020.

### **A-8.c.1 Innovation objectives**

- Incorporate 15%-30% of CO<sub>2</sub> weight in polymers by 2030 (the remainder being bio-based, recycled, CO<sub>2</sub>-based monomers, or fossil).
- Produce polymer materials with a reduced carbon footprint of at least 15% for the first generation of technology (to avoid the development of more energy-intensive technologies).
- Incorporate 20%-40% of CO<sub>2</sub> weight in polymers by 2050 (the remainder being bio-based, recycled, or CO<sub>2</sub>-based monomers).
- Produce new polymeric structures for high performance materials polymers from CO<sub>2</sub> with new properties. At least one large-scale commercial plant by 2025, three demonstration plants, and one multi-purpose plant.

### **A-8.c.2 Impacts**

For the assumptions and methodology underlying our impact estimations reference Appendix E .

#### **Greenhouse gas emissions**

The total polymer market is big; however, only Polyols and PPC can currently be addressed. These product groups collectively accounted for 8-10 Mt of product globally in 2015 (CO<sub>2</sub> Sciences, 2016). Europe is assumed to have a market share of 20%, or around 2 Mt.

Experts estimate that about 50% of these materials can be produced with around 40% CO<sub>2</sub> included in the polymer in 2050. This means that used CO<sub>2</sub> totals ( $2 \times 50\% \times 40\% =$ ) 0.4 MtCO<sub>2</sub> in 2050. The production of raw materials is also avoided, resulting in emission reductions that are even higher (although the exact impact depends on the displaced molecule). To account for this a factor 2 is applied to arrive at 0.8 MtCO<sub>2</sub>. In 2030, only two TRL9 projects will be completed and only a fraction of the total potential is achieved. We assume that this accounts for 0.5% of the potential, or 4 ktCO<sub>2</sub>.

Some of the polyols and PPCs may have functionalities that enable displacement of other polymers, and the resulting total technical potential may be higher. This is uncertain due to the many assumptions about technology development and development of product demand. Additional impact is possible due to the displacement of polyols and PPC from fossil production routes.

## Waste

CO<sub>2</sub>'s use as an alternative carbon feedstock to produce polymers can effectively contribute to the development of a more circular economy. However, because CO<sub>2</sub> is a gaseous effluent it does not contribute towards the target of near zero landfilling and water discharge.

## Competitiveness

There are significant market entry barriers for new polymers. New products are difficult to sell to customers, as their functionality and application need to be tested. To offset transaction costs, better properties or lower costs are needed. Polymers should be produced at lower cost to reduce their market entry barriers.

As the CO<sub>2</sub> displaces more expensive feedstock, there are cost savings. Therefore, this technology could be competitive in the short term. The competitiveness will strengthen when CCU is incentivised.

### A-8.c.3 Programming

Development towards 2030:

- More efficient catalyst: Catalyst optimisation for increased CO<sub>2</sub> conversion, catalyst removal or reuse (A-9.a Next-gen catalysis)
- Use of less purified CO<sub>2</sub>/unpurified CO<sub>2</sub>
- Improved downstream purification (more effective and less costly) (A-10.c Upgrading secondary resources)
- Development of product applications for the new polymers

Development towards 2050:

- Development of new applications for the new polymers
- Polymers from direct valorisation of CO<sub>2</sub>:
  - Polycarbonate-etherols (Polyol): low molecular weight from TRL6 to TRL9 and high molecular weight from TRL4 to TRL9
  - Poly(propylene)carbonate TRL6 to TRL9

To achieve this, a portfolio of projects is programmed that delivers two TRL9 projects before 2030, three between 2030 and 2040, and three more between 2040 and 2050. For this, 11 TRL7-8 projects are needed (more because likely the TRL9 plant will be a multipurpose installation that combines several TRL7-8 technologies). The TRL7-8 projects build on 24 TRL4-6 projects. Fifty TRL1-3 projects are programmed before 2030 to develop new technologies.

### A-8.c.4 Investment needs

We estimate €2 million for each project at TRL1-3; €5 million for each project at TRL4-6; €20 million for demo plant (about 5 kt/y production) TRL7-8, and €100 million for a world scale plant, (50 kt/y) TRL9.

Table 23: Investment needs in € million<sup>88</sup>

Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
2020-2024	25x €2	6x €5	1x €20			€100
2024-2030	25x €2	9x €5	3x €20	2x €100		€355
2030-2040		9x €5	5x €20	3x €100		€445
2040-2050			2x €20	3x €100		€340
Total	€100	€120	€220	€800	€0	€1,240

<sup>88</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

#### **A-8.c.5 Success factors**

- Bio-based or CO<sub>2</sub>-based ways to produce non-fossil co-monomers.
- New types of polymers with improved functionalities.
- Appropriate cost-effective CO<sub>2</sub> capture and purification technologies (see innovation programme A-6.a Flexible CO<sub>2</sub> capture and purification technologies).
- Appropriate evaluation of the environmental impact, especially GHG (including industrial symbiosis, waste heat).
- Policy framework based on the applications (chemical, transport, energy storage), including appropriate recognition of CO<sub>2</sub> emission avoidance in EU ETS (where relevant).

## A-8.d Utilisation of CO to chemicals/fuels

CO is another carbon source that can be captured from various industrial installations, it can also be captured from waste (e.g. plastics, biomass,...) gasification. 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 CO<sub>2</sub>, it can also be used as a feedstock to produce chemicals and fuels. This innovation programme aims to develop and demonstrate the technologies to do this. Such technologies could also be used in biogas installations, as these also produce CO streams.

As with regular CCU options based on CO<sub>2</sub>, there are also many possible routes for CO. For example, one pilot has started to produce ethanol from the CO stream (TRL7-8), and there is also a pilot for CO to synthetic naphtha. Another pilot (BOF2UREA project) uses the CO stream to produce H<sub>2</sub> through a water to gas shift, separates CO<sub>2</sub>, and combines the produced H<sub>2</sub> with N<sub>2</sub> from the furnace to produce ammonia that can be upgraded to urea when combined with the captured CO<sub>2</sub>. The figure below illustrates the many processes that need to work for a project to create the fuel or chemical from CO. Specific challenges are related to the high diluent amount in the steel gas and to specific impurities that need to be removed to allow valorisation.

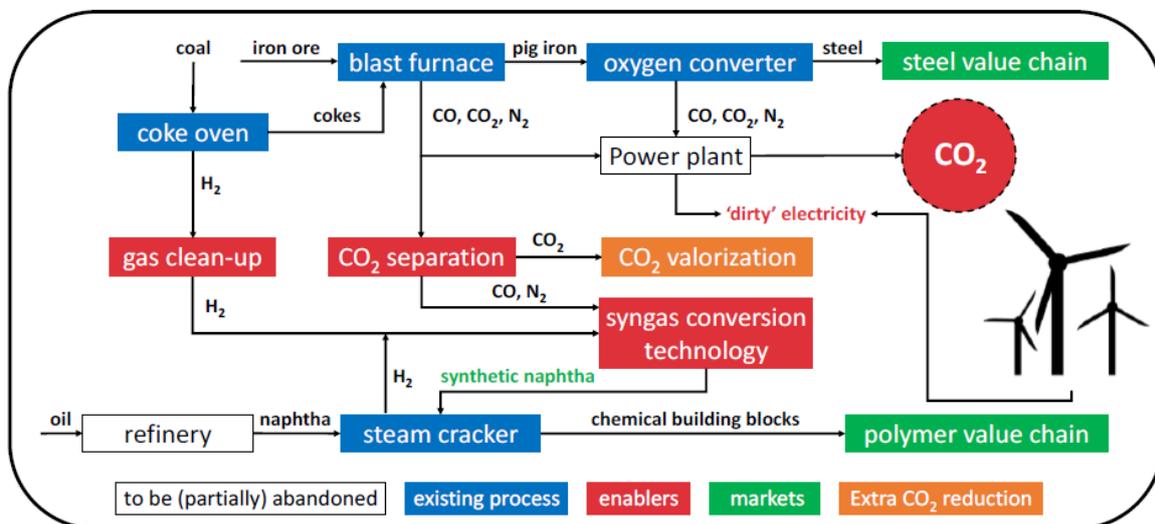


Figure 9: Overview of the Steel2Chemicals project (Ruitenbeek, 2018)

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

Another option is the use of bio-fermentation to convert CO to ethanol and other chemicals. The Steelanol project plans to demonstrate this technology with the production of 80 million litres of ethanol per year, with the option to diversify to other chemical building blocks in the longer term.

### SPIRE project this programme builds on

**C2Fuel** will transform off-gases from the steel sector into fuel by using green H<sub>2</sub>. An additional investment of €30-€40 million is anticipated to take the integrated process to TRL9 by 2027.

#### A-8.d.1 Innovation objectives

Many products can be made from CO, but the production volume should fit with the application and it should be competitive. There are likely two to three technologies that need to be developed to TRL9 (for example, fuels, methanol, and naphtha). This will happen before 2030, as the pilot plants are already running and the first demonstrations are already under

development. The integration of the technologies with the industrial process is essential (e.g. heat integration).

### A-8.d.2 Impacts

For the assumptions and methodology underlying our impact estimations reference Appendix E .

#### Greenhouse gas emissions

The potential of these technologies is determined by Europe’s available CO. 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<sub>2</sub> and has a GHG impact there. This is calculated based on the molar weight ratio (44/28) to be around 5 MtCO<sub>2e</sub>.

If CO streams can 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<sub>2</sub>/yr (DECHEMA, 2017). This equates to CO<sub>2</sub> emissions of 77 MtCO<sub>2</sub>.

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 thus 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 contribute to the development of a more circular economy. However, because CO is a gaseous effluent it does not directly contribute towards the target of near zero landfilling and water discharge.

#### Competitiveness

This technology is only expected to be competitive with fossil fuels when policy justifies a price premium.

### A-8.d.3 Programming

The development is focusing on:

- Gas clean-up (take out impurities that have impact of downstream conversion)
- Gas separation (improved CO<sub>2</sub> removal, development of N<sub>2</sub> removal technologies)
- Developing catalytic technologies to convert waste-based CO sources into valuable chemical products and fuels with improved performance (second generation catalysts)
- Life cycle assessments to assess overall CO<sub>2</sub> impact (including heat integration and industrial symbiosis aspects)

The programme includes three TRL7-8 projects estimated at €100 million each, and then three TRL9 projects that are estimated at €200 million each.

### A-8.d.4 Investment needs

Table 24: Investment needs in € million<sup>89</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Utilisation of CO to chemicals and fuels	2020-2024			3x €100			€300
	2024-2030				3x €200		€600
	2030-2040						€0
	2040-2050						€0
<b>Total</b>		€0	€0	€300	€600	€0	€900

<sup>89</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

#### **A-8.d.5 Success factors**

- Support measures for the production of chemicals and fuels from CO that effectively contribute to carbon circularity
- Policy framework: Recognition of CO<sub>2</sub> emission avoidance in ETS
- Life cycle assessments to assess overall CO<sub>2</sub> impact (including heat integration and industrial symbiosis aspects)
- Hydrogen availability
- Incentives in the renewable energy directive for synthetic fuels

## A-9 Energy and resource efficiency

### A-9.a Next-gen catalysis

Catalysts allow chemical reactions to proceed at lower temperatures and with increased yield and selectivity. A catalyst enables other chemical pathways than those used by the non-catalytic reaction. The inherent change in chemical pathways are 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 room for more than incremental improvement.

All carbon for chemicals and materials will come from CO<sub>2</sub>, biomass, and carbon products recycling (e.g. plastics). New catalysts are needed, for example, to produce hydrocarbons using CCU (see Catalytic conversion of CO<sub>2</sub> to chemicals/fuels in A-8.b), biomass (covered in the BBI), and recycling technologies (see Upgrading secondary resources in A-10.c). The catalysts developed will mainly be applied in the chemical industry, but the refineries, biobased, and recycling sectors will also benefit. New catalysts will enable the improved cross-sectorial exchange of process flows through the utilisation of secondary resources and better control of by-products from chemical reactions with varying secondary resources inputs. The most relevant example is CO<sub>2</sub> flows in H4C.

#### A-9.a.1 Innovation objectives

The objectives are to develop:

- **Catalyst that directly uses renewable energy inputs**, specifically photons or electrons 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<sub>2</sub>O and CO<sub>2</sub> (see Alternative hydrogen production routes in A-5.a and Artificial photosynthesis in A-8.a) (Andrea Álvares, 2017). 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**: Electricity can be used to reduce chemicals and materials directly (see Electrochemical conversion in A-4.a), or electricity can be used to generate alternative energy forms (such as plasma or microwave) that can either accelerate reactions by improving mass transfer efficiencies or by providing different and more intense energy vectors than normally achieved thermally. The latter implies that different bonds can be activated and more reactive intermediates can be accessed, which fundamentally changes the chemistry from the thermal processes. New catalysts (and reactors) are needed to control these new chemistries. These electrocatalysts will enable more selective, robust, and coupled oxidations and reductions, make it possible to create carbon-carbon bonds (olefins) without the use or loss of halogens, provide new routes to polymers and ammonia, and activate less reactive molecules such as CO<sub>2</sub> (the latter as a first step towards CCU (Andrea Álvares, 2017); refer to Utilisation of CO<sub>2</sub> and CO as a building block in polymers in A-8.c);
- **Highly efficient heterogeneous catalysts**: Since heterogeneous catalysts are not in the same phase as the reactants, they have the advantage of being easily separated from reaction products and reused. However, heterogeneous catalysed reactions are generally less selective and have lower yields than homogeneous catalysed 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, 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 new chemistries 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 the 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 improved chemistries. Examples include organocatalysts, enzymes, and biomimetic catalysts. Reproduction of the enzymatic function of methanotrophic 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 multidimensional parameter space, where temperature, pressure, flow rates, and reactant and catalyst concentrations all play a role. The discovery of actual, active catalyst compositions has many permutations. For heterogeneous catalysts, the support, 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 the 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 dataset, it will be possible to develop artificial intelligence or 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<sub>x</sub> and NO<sub>x</sub>, or be able to use dilute CO<sub>2</sub> streams) to improve raw material flexibility and allow more streams to be processed or recycled without a need for upfront purification.

### A-9.a.2 Impacts

For the assumptions and methodology underlying our impact estimations reference Appendix E .

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

#### **Greenhouse gas emissions**

Catalysts can be applied in the water and the chemicals sectors. For the water sector the potential was not determined due to a lack of data. For the chemicals industry, the 2030 reduction potential is estimated to be 0.14%<sup>90</sup> of the sector's emissions, and the 2050 potential is estimated to be 15%.<sup>91</sup> With 124 MtCO<sub>2</sub> emissions in the chemicals sector (see Appendix E ), this implies an impact of at least 0.2 MtCO<sub>2</sub> in 2030 and of 19 MtCO<sub>2</sub> in 2050.

<sup>90</sup> Two out of 21 projects are projected to reach TRL9 in 2020-2024, suggesting that 9.5% of catalysts are ready and 10% of the potential is deployed (see Appendix E). The impact of the projects delivered between 2024 and 2030 is neglected.

<sup>91</sup> Estimate, based on (IEA, ICCA & DECHEMA, 2013), assuming that around half of the catalyst and related process improvements would be the consequence of catalysts.

## **Waste**

The increased selectivity that catalysts offer will reduce the production of by-products. Some of these by-products are sold, others can be reprocessed. There are by-products that can only be incinerated or perhaps landfilled; the latter could be reduced by applying innovative, more selective catalysts. Innovative catalysts enable the potential for higher recovery rates (for example, for homogeneous catalysts).

## **Competitiveness**

If these innovations are developed, the industry's efficiency increases, which is beneficial for its competitiveness.

### **A-9.a.3 Programming**

For all catalysts, the aim is to optimise the yield and selectivity they deliver at practical 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** through the direct utilisation of sunlight is still at TRL2-4 but has the potential of higher efficiencies and lower costs than the coupling of PV production of electricity and the use of that electricity in electrocatalysis. While the bulk of research into photocatalysis is dedicated to hydrogen production from water and the reduction of CO<sub>2</sub>, and while these reactions offer the largest potential environmental benefits, in principle any reaction that is amenable to electrocatalysis will also be amenable to photocatalysis. Any reaction or material transformation that requires a stoichiometric reductant can be modified to use electrons directly generated from sunlight on a photocatalyst. For programming, processes that rely on photocatalytically generated hydrogen are not covered, such as the synthesis of ammonia or reduction of CO<sub>2</sub>.

The aim is to arrive at TRL5 in 2024, followed by significant development 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 developments, since it is essential to control both the formation and eventual reaction of the 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 requires the introduction of pure reactant streams to ensure that the photocatalyst is reacting with the desired substrate and not advantageous impurities. New catalysts 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.
- **Electrocatalysis:** As with photocatalysts, significant development will still be required to realise the industrialisation of electrocatalytic processes. As opposed to photocatalytic processes, there are a few electrocatalytic processes in industry, but these are the exception rather than the rule. New technologies such as microwaves, plasma, and ultrasound (see the Electricity-based heating technologies in A-3.b) are unlikely to operate with the pre-existing catalysts. To implement these technologies, new catalysts need to be developed from the beginning, as different bonds need to be activated, and different process and catalysts are needed to do so effectively; thus, the TRL is low in

most cases, with the aim to be at TRL5 in 2024. Alternative energy forms generated by electricity unlock the new catalysts controlling the new chemistries. These alternative energy forms offer the following features:

- Stable in the presence of higher temperatures and energy fluxes.
- Able to interact rapidly with highly energetic intermediates and control their reactivity.
- Able to direct energy flows to specific bonds and provide new chemistries, for example, a catalyst that (through interaction with a reactant) induces selective bond breaking/forming when heated by microwaves.
- More selective, robust, and cooperative oxidations and reductions.

Furthermore, the following needs to be developed:

- New electrodes designed at the nanoscale, for direct catalytic function at the electrode surface.
- Hybrid electrode/homogeneous catalyst solutions to improve yield and selectivity.
- New non-critical raw material based, high performance and long-lasting electrocatalysts.
- Better electrocatalysts for the valorisation of biomass.
- Bio-electrocatalysis/microbial electrosynthesis for targeted conversions and improved productivity.

For this programme, processes to reduce CO<sub>2</sub> are not covered (as these are covered in innovation programme Catalytic conversion of CO<sub>2</sub> to chemicals/fuels in A-8.b).

#### **SPIRE projects this programme builds on**

**TERRA** developed a tandem electrolytic reactor with the capability to couple an oxidising reaction with a reducing reaction at TRL5. It will need to improve the electrocatalyst to bring it to TRL9 by 2030. The target application is the PET process, and a TRL9 TERRA process could reduce European GHG emissions by up to 10 MtCO<sub>2</sub>/year and make it a more competitive industry. The cost of the electrocatalyst must be reduced by 15% to be economically competitive.

**INCITE** developed a new enzymatic-catalytic process to make special biobased acids in optimised reactor conditions with >50M GHG reductions, 50% less waste, and competitive due to its high efficiency and lower operating temperature.

- **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 required to introduce the required new chemistries to reach the 2050 ambitions. Some examples of the necessary advances in heterogeneous catalysts include the following:
  - Molecular printed catalysts/3D printing or other innovative shaping 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 catalysts, 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.
  - Improved robustness (longer lifetime) and selectivity and higher yields.
- **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 been found. As with heterogeneous catalysts, there is still much to be done. Some examples include:

- 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 direct selective methane oxidation to methanol, leading to improved selectivity.
- 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 that combine multiple homogeneous or heterogeneous catalysts for improved processing.
- The recovery of homogenous catalysts is still an energy and resource intensive endeavour with space for improvement.

The developed catalysts can be applied in the chemical sector, in refineries, for water treatment, and for increased and higher value use of secondary resources.

- The development of AI/machine learning tools to optimise the discovery of new catalysts will need the generation of large datasets and the development of predictive software. This development is expected to reach 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 include the following:
  - 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 of homogenous and heterogenous catalysts covers the programming to develop catalysis tolerant to impurities (e.g. SO<sub>x</sub> and NO<sub>x</sub> and able to process dilute CO<sub>2</sub> streams).

Some of the projects could be applied in new reactor concepts that integrate catalysis and separation. The most efficient integration of a downstream process is to combine it within the reactor where the reaction takes place, which leads to:

- The highest CAPEX reduction (elimination of process steps and thus equipment)
- Milder operation conditions resulting in a lower OPEX (together with circumventing downstream separation)
- Significant gains in resource and energy efficiencies

Application in a modular approach results in maximal flexibility in both size/volume of production and the diversity of chemical reactions that can be addressed.

### A-9.a.4 Investment needs

Table 25: Investment needs in € million<sup>92</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Photocatalysis</b>	2020-2024	10x €2.5	3x €2.5				<b>€32.5</b>
	2024-2030		3x €2.5	2 x €12	1 x €25		<b>€124</b>
	2030-2040			1 x €12	2 x €25		<b>€62</b>
	2040-2050						<b>€0</b>
<b>Electrocatalysis</b>	2020-2024	21x €2.5	6x €2.5	1 x €12			<b>€79.5</b>
	2024-2030		6x €2.5	2 x €12	1 x €25		<b>€64</b>
	2030-2040			3 x €12	5 x €25		<b>€161</b>
	2040-2050						<b>€0</b>
<b>Highly efficient heterogeneous catalysts</b>	2020-2024	7x €2.5	2 x €5	1 x €12	1 x €25		<b>€64.5</b>
	2024-2030	7x €2.5	2 x €5	1 x €12	1 x €25		<b>€64.5</b>
	2030-2040	7x €2.5	2 x €5	1 x €12	1 x €25		<b>€111.5</b>
			2 x €5	1 x €12	1 x €25		
2040-2050			1 x €12	1 x €25 1 x €25		<b>€62</b>	
<b>Fully recyclable homogeneous catalysts</b>	2020-2024	7x €2.5	2 x €5	1 x €12	1 x €25		<b>€64.5</b>
	2024-2030	7x €2.5	2 x €5	1 x €12	1 x €25		<b>€64.5</b>
	2030-2040	7x €2.5	2 x €5	1 x €12	1 x €25		<b>€111.5</b>
			2 x €5	1 x €12	1 x €25		
2040-2050			1 x €12	1 x €25 1 x €25		<b>€62</b>	
<b>Coupling of machine learning/AI and high throughput technologies for catalyst development<sup>93</sup></b>	2020-2024	20x €4	6 x €5				<b>€110</b>
	2024-2030						<b>€0</b>
	2030-2040	7x €4	2 x €5				<b>€38</b>
	2040-2050						<b>€0</b>
<b>Total</b>		<b>€290.5</b>	<b>€232.5</b>	<b>€228</b>	<b>€525</b>	<b>€0</b>	<b>€1,276</b>

### A-9.a.5 Success factors

- Even though catalysts have been developed and used for decades, new disruptive opportunities like photocatalysis and biologically inspired catalysis (such as enzymatic and biomimetic approaches catalysis) continue to emerge, and their development enables the transition and makes it more efficient, reducing the need for scarce goods like renewable energy.
- Adjustment of international legislation procedures and rules to the new modular concept is necessary,
- To become cost-competitive and to reach industrial scale, new intelligent equipment designs and standards need further development.

<sup>92</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined; investment needs only include the operation and testing, not the production system of the catalysts; photocatalysis and electrocatalysis for CO<sub>2</sub> utilisation and photocatalysis for H<sub>2</sub> production is programmed in innovation programmes Artificial photosynthesis in A-8.a, Catalytic conversion of CO<sub>2</sub> to chemicals/fuels in A-8.b, and Alternative hydrogen production routes in A-5.a

<sup>93</sup> No TRL7-9 projects programmed for this technology, as the application of the catalyst would be done in other TRL7-9 projects (as programmed in the lines above in this table).

## A-9.b Breakthrough efficiency improvement

This innovation programme focuses on breakthrough efficiency improvements in industrial processes that go beyond the regular incremental improvements.

### SPIRE projects this programme builds on

**IMPROOF** leads to a cost-effective improvement of steam cracking furnaces through improved heat transfer, 3D-profiles, reactors, and oxyfuel combustion. It will lead to increased competitiveness and nearly fully reduce NO<sub>x</sub> emissions (16.3 x 10<sup>3</sup> tpa NO<sub>x</sub>) of current European furnaces. Additional investment of €30-€50 million is estimated to achieve TRL9. Emitted CO<sub>2</sub> (thanks to oxyfuel) can be reused in CO<sub>2</sub>-use installations due to its high purity

**DREAM** demonstrates at TRL7 a radically improved architecture for ceramic industrial furnaces. It leads to 5% waste reduction and can be further developed to TRL9.

**ECCO** brings a new solution for the curing oven in a coil coating process leading to increased production flexibility and energetic efficiency increase. It is now developing towards TRL5 with potential to meet TRL9 in 2027 and will lead to 20% reduction of manufacturing costs.

**MORSE** is optimising raw material and energy consumption in the steel industry by controlling resource input and product quality throughout the production process. Development to TRL9 is expected by 2024, leading to 10% reduction in energy use and 25% reduction in yield losses (80% for chromium alloys).

**SUPREME** develops an integrated, flexible, and sustainable process for powders manufacturing in the ferrous and non-ferrous industry and enables a strong reduction in raw material losses. It will bring gas atomisation to TRL8 and ball milling to TRL7 with around 30% GHG-emission reduction and 25% reduction in material losses. Costs are reduced between 5% and 25%.

### A-9.b.1 Innovation objectives

- **Develop and deploy process intensification solutions:** Process intensification is defined as "Any chemical engineering development that leads to a substantially smaller, cleaner, safer, and more energy efficient technology" (Reay, 2008). Examples of process intensification include but are not limited to:
  - Change from batch to continuous flow processes
  - Microreactor systems, including 3D printed microreactors that provide better mass transport and contact times
  - Integrated membrane reactors and membrane separations in continuous processes
  - Continuous reactive separation processes
  - Distillation intensification, such as high gravity and enzymatic distillation
  - Reactive extrusion
  - Evaporative crystallisation
  - Efficient thermal separation technologies such as membrane distillation (combining low temperature thermal energy with electricity, enabling the use of waste heat, already proven to produce process water and for the recovery of valuable materials)
  - Innovative integrated drying and heat recovery processes
  - Wood chemical pulping technologies at much lower temperature, pressure and/or reaction time
  - Develop sensors and models to improve the energy efficiency of paper production processes

Smaller equipment facilitates better process control and selectivity, lower investments, and reduced energy and feedstock use. There is a large bulk of process intensification solutions at various TRLs, 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 3D printing), there is a rationale to focus on:

- Developing 3D printed process equipment that reduces equipment size and improves mass and energy transfer and thus reactivity and product/by-product quality.
- Coupling of reduction and oxidation processes in electrochemical reactions, where in the electrolysis to produce hydrogen oxygen typically can be produced as well. Oxygen is normally produced using around 200 kWh electricity/tonne of oxygen (Alavandi, Seaba, & Subbaraman, 2018).
- Other disruptive energy and resource efficiency improvements involving hybrid or coupled processes, such as integrated reaction and separation, reactive extrusion, and microfluidic reactors.
- **Develop new processes that allow better utilisation of heat upgrading technologies.** These are technologies that increase the vapour quality by removing air and/or contaminants as to allow efficient use of heat pump technologies: e.g. superheated steam drying, air/vapor separation, removal of solid contaminants).
  -
- **Develop processes that significantly reduce energy consumption in separation or drying processes:**
  - Processes and process additives that need significantly less water
  - Processes for improved mechanical dewatering before drying
  - Water removal processes that require no evaporation, e.g. with sorption or super critical CO<sub>2</sub>
- **Develop completely new process routes for manufacturing the same product**
  - E.g. Paper making without water, requiring development of new processes for all unit operations (disparging, cleaning, web formation, etc.)
- **Develop processes that minimise non-recyclable waste:** No process is 100% efficient, but improved process control is needed to ensure that the outputs from all 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. This innovation objective includes the following:
  - Processes that 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, for example, flexible hydro and iono-metallurgical processes.
- **Develop modular process solutions:** To enable resource efficiency and H4C, some processes will need to be executed at a smaller scale than usual, and thus smaller scale modular plants need to be developed. For example:
  - To avoid transporting huge amounts of low density waste, convert the waste into pyrolysis oil in small localised units that can 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 biogas, which can then be fed into the gas network. This conversion eliminates the need to transport biomass over significant distances).
  - The trend towards decentralised and tailor-made products can lead to demand for modular process solutions.
  - 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.

## A-9.b.2 Impacts

For the assumptions and methodology underlying our impact estimations reference Appendix E .

### Greenhouse gas emissions

Modular plants do not directly lead to GHG emission reductions, but energy can be saved through the avoidance of low density waste transportation and the more efficient use of renewable energies. These plants will enable H4C and many of the recycling and use of secondary material options mentioned in the other innovation programmes. The goal is to have smaller modular plants that are as efficient as the larger established ones.

Combined with the innovation programme, Upgrading secondary resources (A-10.c), this innovation programme can significantly reduce the amount of waste produced by the process industry sent to landfilling.

Modular plants do not lead to a waste reduction but enable H4C and many of the recycling and use of secondary material options mentioned in the other innovation programmes.

The table below depicts the GHG impact estimation. The impacts due to process intensification and due to reducing non-recyclable waste are estimated separately per sector.

Sector	Current Emissions in EU, MtCO <sub>2</sub> e	Emissions reduction by process intensification 2030/ 2050 <sup>94</sup> , %	Emission reduction by reduction of non-recyclable waste, 2030/ 2050, %	Emission reduction impact 2030, MtCO <sub>2</sub> e	Emission reduction impact 2050, MtCO <sub>2</sub> e
Cement	41	Small / <5%	Small / 2%	Small	<2.9
Steel	190	1% / 15%	Small / 2%	2.0	32.3
Chemicals	124	1% / 20%	Small / 2%	1.3	27.2
Ceramics	16	Small / <5%	Small / 2%	Small	<1.1
Non-ferrous metals	10	Small / <5%	Small / 2%	Small	<0.7
Minerals	6	Small / <5%	Small / 2%	Small	<0.4
Water	0	Not determined	Not determined	Not determined	Not determined
<b>Total P4Planet</b>	<b>386.2</b>			<b>1.3</b>	<b>&lt;64.6</b>

### Competitiveness

Process intensification has a positive impact on competitiveness, especially for greenfield investments, due to the increased energy and resource efficiency and the lower CAPEX.

## A-9.b.3 Programming

### Process intensification:

- For 3D printed process equipment (currently at TRL3), challenges include:
  - Complicated programming (there is a need to develop computational strategies to optimise reactor shapes; this could be tackled in a CSA in 2021; €1-2 million).
  - Limited resources for 3D printing.
  - Need for new 3D printing technologies,, which aim to increase the printing speed, improve mass and energy transfer in printed equipment, and decrease the material (metal powder) use and cost.
  - Scale up 3D-printed reactors. While these reactors are commercially available already at small scale, scaling up is non-trivial and there are a host of unaddressed safety issues including reactant flow and heat management.

Development of:

<sup>94</sup> Includes other disruptive other energy efficiency options.

- Microreactor systems, including 3D printed microreactors that provide better mass transport and contact times
- Integrated membrane reactors and membrane separations in continuous processes
- Continuous reactive separation processes
- Distillation intensification, such as high gravity and enzymatic distillation
- Reactive extrusion
- Evaporative crystallisation
- Efficient thermal separation technologies such as membrane distillation (combining low temperature thermal energy with electricity, enabling the use of waste heat, already proven to produce process water and for the recovery of valuable materials)
- Innovative integrated drying and heat recovery processes
- Wood chemical pulping technologies at much lower temperature, pressure and/or reaction time
- **Develop sensors and models to improve the energy efficiency of paper production processes**
- **Develop new processes that allow better utilisation of heat upgrading technologies.** These are technologies that increase the vapour quality by removing air and/or contaminants as to allow efficient use of heat pump technologies: e.g. superheated steam drying, air/vapor separation, removal of solid contaminants).
  -
- **Develop processes that significantly reduce energy consumption in separation or drying processes:**
  - Processes and process additives that need significantly less water
  - Processes for improved mechanical dewatering before drying
  - Water removal processes that require no evaporation, e.g. with sorption or super critical CO<sub>2</sub>
- **Develop completely new process routes for manufacturing the same product**
  - E.g. Paper making without water, requiring development of new processes for all unit operations (dispersing, cleaning, web formation, etc.)
- 
- Coupling processing steps, such as reaction and separation or pre-purification and reaction, as supported by life cycle assessment of the new process versus state-of-the-art.
- New processes that integrate multiple reaction steps in a single reactor, for example, coupling secondary reactions with equilibrium-limited reactions (use of Le Chatelier's principle) to increase reactant conversion, increase product yields, and decrease reactant recycling.
- Learnings will be shared in a non-technological program.
- These activities can build on the learnings from innovation programme, Electrically driven separation (A-4.b), for membrane development.

#### **SPIRE projects this programme builds on**

**MEMERE** developed a O<sub>2</sub> separating membrane for oxidative coupling of methane to ethylene at TRL5 leading to 40% GHG reduction and 25% waste reduction. The realisation of a TRL9 facility by 2028 will give 40% reduction in GHG emissions and 25% reduction in waste and a need to focus on the reduction of costs by at least 15%.

**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. Processes can be optimised to provide even tighter product and by-product specifications. Advances in

digitalisation will result in much of the technological innovation to minimise non-recyclable waste. Specific goals include the following:

- Develop processes that adjust in real time to changes in feedstock and energy inputs, without affecting the quality of the final product.
- Develop tighter processing controls to minimise out-of-spec materials and more stringent product and by-product specifications.
- Enable 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. The current TRL is 4-7. 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 are:

- 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, etc.).
  - Miniaturisation and cost reduction of equipment (especially sensor technology, automation, process control, switch cabinets, etc.).
  - Smart equipment in intensified upstream and downstream processing with additional control opportunities, small and smart laboratory equipment for measuring and optimising intensified process steps.
- Operation of Modular Plants (Plug and Produce):
  - Remote operation (safety and authority engineering aspects).
  - Modular Automation in continuous operation as well as process orchestration layer.
  - Expand to new process areas (e.g. decentralised biorefineries, etc.).
  - New business concepts (e.g. life cycle management, rental, maintenance, etc.).
- The following innovation needs will be executed in a non-technological program:
  - Methods and Tools:
    - Life cycle analysis for modular plant concepts and their operating models (e.g. rental of modules, shared use, shared maintenance, etc.)
    - (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 to 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, etc.)

**SPIRE projects this programme builds on**

**INSPIRE** developed modular and decentralised processing in customer-driven value chains at TRL6-7 with expected decrease in costs of 6%.

#### A-9.b.4 Investment needs

Table 26: Investment needs in € million<sup>95</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Developing and deploy process intensification	2020-2024		10x €3	3x €13	4x €25	€1.5	€170.5
	2024-2030		10x €3	3x €13	5x €25		€194
	2030-2040			3x €13	3x €25 +3x €25		€189
	2040-2050						€0
Develop processes that minimise non-recyclable waste	2020-2024		10x €3	3x €13	3x €50		€219
	2024-2030		10x €3	3x €13	3x €50		€219
	2030-2040			3x €13	3x €50 +3x €50		€339
	2040-2050						€0
Development of modular process solutions	2020-2024		20x €5	4x €10	2x €20	1x €7	€187
	2024-2030			6x €10	4x €20		€140
	2030-2040				6x €20		€120
	2040-2050						€0
<b>Total</b>		<b>€0</b>	<b>€220</b>	<b>€334</b>	<b>€1,215</b>	<b>€8.5</b>	<b>€1,777.5</b>

#### A-9.b.5 Success factors

- Digitalisation in process development (see the innovation programme, Digital process development and engineering in A-13.b)
- 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

<sup>95</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-10 Circularity of materials

### SPIRE project this programme builds on

**NOVUM** develops a cellulose-based thermoplastic 3D-printable with fused deposition modelling (FDM) at normal process temperatures (200 °C) for electrical insulation in power transformers through thermoforming and foam forming, providing a step-change in the design and production of power transformers. The material development is at TRL5 while the forming technology is at TRL4. It leads to GHG reduction as the coating material is biobased and it has a high potential for competitiveness as it has less steps and less labour costs. It can go up to TRL9 by 2025. However, it still needs an intermediate update to TRL7.

### A-10.a Innovative materials of the process industries

#### A-10.a.1 Innovation objectives

The objective is to develop new processes and materials that optimise technical and the ecological performance over their full life cycle.

This innovation program focuses on in situ functionalisation and defunctionalisation of materials, as this allows the postponement of circular movement. This could include functionalities such as self-healing cement or paint.

This innovation programme's purpose is not:

- To develop new sustainable materials (like bio-based materials) to replace currently available less sustainable materials, as this is not in the scope of P4Planet.
- To stimulate all the regular (ongoing) process industry's material development, which is part of their normal business model anyhow.
- To design materials in such a manner that recycling/upcycling is enabled, as this is part of the next innovation programme (Inherent recyclability of materials in A-10.b).

#### A-10.a.2 Impacts

This innovation programme's key GHG emission reduction and resource efficiency impacts are in other, non-process industry sectors or are indirect. If they are indirect, this is because the materials might reduce in demand 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).

The production of waste will decrease because of this innovation program. By increasing the added value per product, the European process industry's competitiveness is (potentially) increased. The programme adds to a material's value at the normal end of its lifetime.

#### A-10.a.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 the accelerated development of materials, enabling breakthrough and meaningful in situ functionalisation and defunctionalisation of materials, in whatever manner that eliminates GHG emissions and landfilling.

### A-10.a.4 Investment needs

Table 27: Investment needs in € million<sup>96</sup>

Activity	Timing <sup>97</sup>	TRL1-3	4-6	7-8	9	Non-technological	Total
Innovative materials of the process industries	2020-2024	20*€2	6x €5	3x €10			€100
	2024-2030	20*€2	6x €5	3x €10	3x €40		€220
	2030-2040	20*€2	6x €5	3x €10	3x €40		€400
			6x €5	3x €10	3x €40		
2040-2050				3x €40		€120	
<b>Total</b>		<b>€120</b>	<b>€120</b>	<b>€120</b>	<b>€480</b>	<b>€0</b>	<b>€840</b>

### A-10.a.5 Success factors

- Life cycle assessment 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, including an obligation to share reliable data for the innovative materials developed.

<sup>96</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined; the programmed investments are an average estimate, in reality this will vary per project.

<sup>97</sup> These numbers only include programmes dominated by environmental performance, and assuming companies' appetite for involving public funding for their product development.

## A-10.b Inherent recyclability of materials

The complexity of sophisticated products makes it difficult to recover secondary raw resources of appropriate quality for reuse. The materials produced by the process industries are designed to fulfil the increasing functionality requirements rather than be reused or recycled. Recycling applicability is hindered by the heterogeneity of the waste streams and by the complexity of product parts composed of several materials, such as multi-layers and composites. For this innovation program, process industries will work closely with brand owners and service providers downstream to ensure that the materials developed by the process industries will be appropriate for the circular economy without compromising on performance. Life cycle assessments need to inform decision-making for the best end-of-life treatment. For the moment, incineration can be an option, leading (in some cases) to lower GHG emissions than current recycling offerings, especially when energy is recovered from the incineration process or when the emitted is CO<sub>2</sub> captured and used.

### A-10.b.1 Innovation objectives

This innovation programme aims to enable the manufacturing industry to make more recyclable products while maintaining performance, through the following:

- **Developing recycling friendly materials by reducing the complexity and heterogeneity of components:** The functionality of today's products is ensured by a 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, paper or concrete) make recycling of these materials difficult or impossible. Advances need to be able to replace these multicomponent, inherently difficult-to-recycle materials with single materials or a suite of materials that are more compatible to recycling. This requires a deep understanding of the materials and their journey through the circular economy (as well as how they are treated at the end of their life).
- **Developing smart connections between different materials:** These connections enable functionality during a material's lifetime but can be disconnected at the end of a materials/products lifetime. This enables recycling of the different connected materials.

### A-10.b.2 Impacts

#### *Greenhouse gas emissions*

The recycling processes should be operated on GHG emission-free energy, and their energy use should be optimised. This replaces the current GHG emissions associated with the production of virgin materials.

#### *Waste*

The resource efficiency will increase because of this innovation programme, and the amount of landfilled materials will decrease because of the longer use and inherent recyclability of materials.

#### *Competitiveness*

The competitiveness of the process industry increases when the resource efficiency increases, while maintaining its functionality. The value of the materials produced increases as materials are kept in the loop longer.

### A-10.b.3 Programming

- **Developing recycling friendly materials by reducing the complexity and heterogeneity of components:** This includes developing an organic wheel, indicating which combinations of organic materials can and cannot be separated, and informing which combinations should be pursued in future material development. The aim is to

develop 12 TRL9 projects (new materials) in this program, including new, recycling-friendly composites (for example, thermoplastic composites) with enough functionality.

- **Developing smart connections between different materials:** This includes smart glues (materials), but also materials that are responsive to mechanical, thermal, or electromagnetic stimuli. Development of these processes is beginning and is expected to continue over time.

#### A-10.b.4 Investment needs

Table 28: Investment needs in € million<sup>98</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Developing recycling friendly materials by reducing the complexity and heterogeneity of components</b>	2020-2024	20*€2	6x €5	3x €10		1x €10	€110
	2024-2030	20*€2	6x €5	3x €10	3x €40		€220
	2030-2040	20*€2	6x €5 6x €5	3x €10 3x €10	3x €40 3x €40		€400
	2040-2050				3x €40		€120
<b>Developing smart connections between different materials</b>	2020-2024	20*€2	6x €5	3x €10			€100
	2024-2030	20*€2	6x €5	3x €10	3x €40		€220
	2030-2040	20*€2	6x €5 6x €5	3x €10 3x €10	3x €40 3x €40		€400
	2040-2050				3x €40		€120
<b>Total</b>		<b>€240</b>	<b>€240</b>	<b>€240</b>	<b>€960</b>	<b>€10</b>	<b>€1690</b>

#### A-10.b.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.

<sup>98</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-10.c Upgrading secondary resources

### **SPIRE projects this programme builds on**

**NONTOX** allows the recycling of the polymers and metals from WEE, ECV, and CDW. It significantly reduces CO<sub>2</sub> emissions and will lead to 3-4 Mt/y waste reduction. It can start at TRL6 in 2023. Insufficient and unreliable data about the waste and inconsistent feedstock composition create some hurdles for the project.

### **A-10.c.1 Innovation objectives**

There is significant potential to improve the use of secondary resources in the process industry. To a large extent, this is due to the development of better separation and sorting technologies, which are often supported by digital solutions. This includes bio-separation, reactive separation, hybrid separation, and electrochemical separation and purification of materials (including catalysts). In the programming section, the innovation objectives are outlined by waste category.<sup>99</sup>

While some of the recycling technologies are sector specific, there are many cross-sectorial elements.

The objectives of this innovation programme rely on advanced monitoring and sensing in the process industry and in (new) value chains, as developed in the programme, Intelligent material and equipment monitoring in A-13.d, and in the programme, Autonomous integrated supply chain management in A-13.e.

### **A-10.c.2 Impacts**

#### ***Greenhouse gas emissions***

There will be significant energy savings and reductions in GHG emissions. Emissions reductions are the result of less intensive processing of secondary raw resources, compared to the processing of ores and minerals to produce primary resources as seen in the aluminium and steel sectors. Reaching the goal of a climate neutral European society becomes easier with a significant increase in the use of secondary raw materials. Increased use of secondary resources has cross-sectorial applications as all P4Planet sectors will benefit from the reuse of processed secondary resources either within their own sectors or across the sectors. To stay on track towards climate neutrality, the new processes (separation, use of secondary resources) should use renewable energy sources.

#### ***Waste***

The reduction of landfilling depends on innovation and on how member states organise waste disposal; the latter has not been quantified. Our approach considers all waste categories and outlined innovation objectives to increase their use as secondary resources (upcycling), thus concurrently reducing landfilling, and should have the potential to significantly reduce landfilling. The programmed coordinated support action should also map the attainable reduction of landfilling. There will likely remain a need (at least for the decades to come) for safe landfilling to deal with the most difficult to separate materials. Enhanced landfill mining (not programmed here) also provides the potential to process or remove already landfilled mass.

#### ***Competitiveness***

Increased use of secondary resources can enhance the competitiveness of the European process industry (in many cases, this is more energy efficient than the current processes). The new positions that become available in new value chains could—if supported by an appropriate policy scheme—offer new possibilities for industries currently under pressure from competition from outside Europe.

<sup>99</sup> For the readability, these are described in combination with the programming.

### A-10.c.3 Programming

The programming collected suggestions for projects that are increasing the use of secondary resources, and matched these with a more general framework based on an assessment of the innovation needs to increase using the various waste categories relevant for P4Planet as secondary resource (quantities are order-of-magnitude-estimates for the amount of this waste generated in Europe, based on Eurostat data; more information on these waste streams is in Appendix E). This programming is based on average costs for recycling innovation projects and delivers various TRLs (no attempt has been made to determine the required investments in innovation projects for individual projects, waste categories, or sectors), and on simplifications that concern current TRLs (reference Appendix E):

- **Improve data:** Data completeness and accuracy (in Eurostat) can be improved. For example, waste streams that are sent to recyclers and (partially) subsequently landfilled can be accounted for. The level of granularity of the programming must be improved with a large, sufficiently funded, exercise mapping the exact recycling (upcycling) opportunities for each of the waste streams available, with a higher level of detail than presented in the Eurostat database. This will require detailed data digging that maps the production of waste streams and the potential to use it. It will require a thorough view (established in a broad stakeholder process) on the effect of designing for recycling (reference the innovation programme, Inherent recyclability of materials, in A-10.b), to establish the waste streams that will no longer be generated. The resulting insights should be made public and should be presented so companies (in H4C) can understand how to use their side streams effectively, eliminate waste streams, and use more/only secondary resources.
- **Spent solvents** ( $\pm 2$  Mt/yr) often are already recycled or incinerated with or without energy recovery. Regeneration of spent solvents essentially means purifying them. This is often done by (energy intensive) distillation. Innovations (for example, membranes) increase the energy efficiency, yield, and purity and expand the possibilities to treat spent solvents (used currently and used in the future); this increases the competitiveness of regeneration of spent solvents. The TRL for new processes typically lies between 5-7 at most; the aim is to deliver five TRL9 projects. The new technologies can also be rolled out in new business models (leasing solvents rather than buying them), for example in H4C.
- **Acids, alkaline, or saline wastes** ( $\pm 6$  Mt/yr) are already recycled, which can be completed using end-of-pipe technologies like electrodialysis. The energy consumption required to purify concentrated streams is limited, but the selectivity and the range of effective concentrations is to be improved. New technologies, like ion-exchangers, membranes, and dialysis, can split these waste streams energy efficiently in acids and bases up to low concentrations with an increased selectivity. Their current TRL lies around 5, with the aim to deliver five TRL9 projects;
- **Plastic wastes and Used oils** ( $\pm 18$  Mt/yr and  $\pm 4$  Mt/yr): Plastic waste comes from a large variety of applications that includes packaging, while used oils are mineral-based, synthetic oils, and biodegradable engine oils, and originate from the refining process and from the mechanical engineering and maintenance of vehicles. Plastic waste can also be collected from municipal solid waste (MSW), industrial plastic waste, and plastic litter from nature.

Plastics are already recycled mechanically, where, after collection the waste is valorised, granulated, melted, and recycled, sometimes leads to downgrading material. Mechanical recycling is often cheaper and more energy efficient than chemical recycling. The mechanical recycling of chemicals does not usually occur in the process industry, but rather in the manufacturing industry. Nevertheless, the process industry can become indirectly involved when it comes to tracking and sorting mixed municipal waste.

Plastics that cannot be recycled mechanically (after improving on design for recycling, in innovation programme, Inherent recyclability of materials in A-10.b, and with innovations outside the scope of the roadmap increasing the applicability of mechanical recycling)<sup>100</sup> and used oils can be recycled chemically.

Chemical recycling is still in its infancy but has great potential and can be used to process biowaste. There are several technological routes for chemical recycling, and at this low stage of development it is unclear which routes offer the most potential. Furthermore, the selected technology depends on the local situation (for example, on the presence of an existing naphtha cracker, and [scale of] availability of waste plastics). This innovation programme aims to develop all routes to a maturity level where selection of most promising technologies is possible. The various routes include:

- Thermochemical recycling, such as gasification and pyrolysis, where waste is processed to obtain syngas and oil, respectively – substances that can be used to produce fuels and chemicals and substitute crude oil. The advantage of these technologies is that they allow processing relatively heterogeneous/mixed waste streams:
  - **Gasification** 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 at a lower TRL, this technology could perhaps be electrically driven (refer to innovation programme, Electricity-based heating technologies, A-3.b).
  - **Pyrolysis** uses high temperatures to break down the material. The pyrolysis technologies are, mainly for PE, PP and PS, in TRL5-8. Pyrolysis process for more complex polymer composition with e.g. hetero-atoms are at lower TRL. A very important aspect is the energy consumption of the processes which must be lower as the fossil based route. Challenges are related to making the technology more robust for fluctuating waste composition and developing better dewatering technologies. Potentially at a lower TRL, this technology could perhaps be electrically driven (refer to innovation programme, Electricity-based heating technologies, A-3.b).<sup>101</sup> The produced pyrolysis oil can be used after hydrogenation as secondary resource to replace virgin naphtha and produce high value chemicals (such as ethylene and propylene).
- Chemical leaching and depolymerisation breaks a material down to polymers or monomers. This method avoids downgrading waste as building blocks are recovered that can be used to produce new material equivalent to virgin materials based on fossil resources. A depolymerisation process has already been operated for polyesters and polyamides in the 90s (TRL9), but most applications still have low TRLs (for PET: TRL6; for some other promising plastics: TRL3) and need to be better developed as they have high impact resource efficiency and circularity potential. Good tracking and sorting technologies also need to be developed, for example, for chemical recycling, a very clean and homogeneous waste stream is necessary.
- **Biotechnological** recycling, in which enzymes or microbes are used to break down materials. This option still needs fundamental research on lower TRLs.
- **Solvolytic**, a process that can be used to separate composite plastics chemically using solvents. This technology is at TRL3-5 and is behind for polyolefins.

<sup>100</sup> For example (some) multilayer plastic packaging.

<sup>101</sup> Note that (Suschem, 2019) gives a lower TRL: "Pyrolysis technologies are currently at TRL 3-5 with a range of maturities that go from concept all the way to small demo plants". (Broeren, 2019) indicates a TRL of 8 for conventional pyrolysis and of 5-7 for integrated hydro-pyrolysis.

- **Electrochemical**, an option linked with the innovation programme, Electrochemical conversion.
- **Advanced separation technologies** to isolate disturbing contaminants from recycled materials.

Plastics can also be converted into charcoal (torrefaction). General development needs are required to further innovate chemical recycling, and include:

- The quality of waste streams is an enabler of (mechanical and chemical) plastics recycling. It is essential to develop effective tracking, sorting, and purification technologies as well, and to be able to deliver the appropriate streams for the mechanical and chemical recycling processes (as for most/all waste streams). The presence of hetero atoms (all atoms other than C and H) is a specific challenge for chemical recycling processes:
  - Oxygen atoms can be converted to CO (syngas) or can be hydrogenated
  - Presence of chlorine atoms needs to be avoided in many processes (thus there is a rationale to keep PVC separate)
  - Presence of nitrogen atoms needs tailor made solutions
  - Presence of trace of heavy metals can foul catalyst surfaces

Technologies that turn CO<sub>2</sub> into chemicals can also be considered recycling, but these are not included here as they are already part of the innovation programmes, Artificial photosynthesis (A-8.a) and Catalytic conversion of CO<sub>2</sub> to chemicals or fuels (A-8.b).

Current TRL ranges between 3 and 7-9; the aim is to deliver 10 TRL9 projects.

#### **SPIRE projects this programme builds on**

**ISOPREP** is using a solvent-based recycling technology to reprocess polypropylene waste into new polypropylene resin that has analogous quality to virgin resin. The result will be a 22% reduction in GHG emissions and a 46% reduction in cost as compared to other recycling technologies. Further investment of €2 million is needed to reach TRL9.

**MMATWO** delivers a PolyMethylMethacrylate recycling value chain based on 2G-PMMA production. It leads to 78% reduction of GHG emissions, to 90% reduction of water consumption and 73% of energy reduction. It can bring the recycling of PMMA to 95%. It will be at TRL7 by 2022 with potential to go to TRL 9 by 2025.

- **Chemical and medical waste and sludges and liquid waste from waste treatment** (±17 Mt/yr and ±10 Mt/yr): These categories include a variety of chemicals, paints, medicines, catalysts, spent ion-exchanges, off-spec products, and organic and inorganic components. Around 35%-45% of these waste streams are sent to recyclers, while 45% of the sludges are landfilled. For example, in the production of aluminium, 20 kg of carbon waste is produced per tonne of primary aluminium (mostly from the pot lining), which is only partially reused. Two innovation streams will be pursued:
  - To better valorise these streams, entirely new (current TRL1) separation technologies are needed. The aim is to deliver 10 TRL9 projects, unlocking new separation possibilities.
  - In cases where chemical recycling cannot be applied, organic sludge could be anaerobically digested. This technology is already at TRL9, but low energy pre-treatment can increase the overall efficiency (current TRL7). Mixing in the reactor can be improved with a management system (current TRL7) and digestate valorisation can be enhanced by improving the separation of liquids, nutrients, and fibres (current TRL not higher than 5). The aim is to deliver five TRL9 projects.

Potential problems for medicines are related to the evolution of antibiotic-resistant bacteria, an incentive to incinerate these still exists.

- **Rubber wastes** ( $\pm 3$  Mt/yr) are about recycling of tires. These are composed of chemicals (like carbon black and rubber), minerals (filler) and steel (wire). Separation is the challenge. Current tire recycling often indicates downcycling. Upcycling requires better separation of the components and this can be achieved by dissolution, which requires a different design of tires (current TRL4 at most). The aim is to deliver three TRL9 projects;
- **Healthcare and biological waste** ( $\pm 2$  Mt/yr) consist of biological waste from the healthcare of animals and humans. This waste is largely incinerated. Some streams (bacteria, viruses) will continue to be incinerated, while anaerobic treatment may be the best solution for other streams. Gelatine from animal bones is already recycled successfully; other streams could be recycled with new extraction processes (current TRL3-5). The aim is to deliver four TRL9 projects.
- **Metal waste (ferrous, non-ferrous, mixed)** ( $\pm 75$ ,  $\pm 9$ ,  $\pm 15$  Mt/yr), sometimes in combination with other materials (like minerals), are largely recycled. Other, less concentrated waste streams also contain (non)ferrous metals. Not all combinations of metals can (currently) be separated; these combinations are mapped in the metal wheel. Consequently, some of the waste metals sent to recyclers is landfilled. A Coordinated Support Action (CSA) will explore alternatives for those combinations of metals that cannot be recovered. New separation technologies (the current TRL is very low) will be developed, with the aim to deliver 15 TRL9 projects. These include:
  - For steel:
    - Innovative technologies for characterisation (sensors, smart software tools) of steel scrap.
    - Innovative collection and sorting technologies for the collection of steel (e.g. robotic cutting and handling or laser induced breakdown spectroscopy to allow automated sifting of mixed waste streams).
    - New technologies to purify molten scrap steel (e.g. sulphide matte, chloride slagging, preferential melting).
  - For non-ferrous metals:
    - Separating (sometimes toxic) impurities (molybdenum, chromium, zinc) in scrap, including bioleaching and de-zincing coated steel sheets.
    - Advanced sorting technologies (like Eddy-current separation, LIBS, and alloy-based [e.g. by using X-ray (European Aluminium, 2016)] technologies at affordable cost) for aluminium.
    - Low cost process for melt aluminium purification includes the application for possible by-products, e.g. techniques to remove some specific impurities like magnesium, iron, lead, lithium, silicon and titanium (European Aluminium, 2016).

Standard technologies for non-ferrous metal recovery are at TRL6-7 while bioleaching is at TRL3-4.

- **Wood wastes** ( $\pm 55$  Mt/yr): Clean wood is already recycled into materials like chipboard; no innovations are pursued here. Recycling of waste wood from the wood processing industry is part of the scope of the BBI, and is not covered here. Polluted wood (from industrial and urban waste) contains significant amounts of fossil-based carbon from coatings, paints, plastics, and preservatives and can be recycled using the innovative processes described previously (among others, chemical recycling). New separation/dissolving (like dissolving cellulose, followed by depolymerisation of the remaining lignin fraction, followed by the separation of the inorganics and the pyrolysis of the organics) processes are currently around TRL3; the aim is to deliver nine TRL9 projects.

### **SPIRE projects this programme builds on**

**REHAP** is fully replacing fossil-based chemicals with agro-forestry waste materials for 1,4 BDO resins and bio polyesters for adhesives, foams, and plasticisers. The technology is at TRL6-7 and can be realised at TRL9 by 2025. Energy efficiencies will be improved by 30%, with concomitant reductions in the use of fossil fuels and GHG emissions.

- The **Textiles** sector ( $\pm 2$  Mt/yr Textiles waste) is actively working on new recycling processes, including the recycling of jeans with addition of cellulose-based fibres, to which pigments are deposited electrochemically. Polyesters from textiles could be recycled directly into new polyester products with a new (chemical recycling) process where remaining components could be turned in pyrolysis oil or gasified. While the current TRL is low,<sup>102</sup> the aim is to deliver one TRL9 process for this concept; this falls under the scope of SPIRE due to its links with the chemical (recycling) sector.

### **SPIRE projects this programme builds on**

**RESYNTEX** developed an integrated textile waste degradation pilot plant (30 tonnes per year) to produce terephthalic acid and protein hydrolysate at TRL6. It is ready for value chain support at TRL9 by 2025. Accompanying value chain support will reuse 80% of all wastewater, contributing significantly to waste reduction.

- From **discarded equipment (excluding batteries, accumulators and discarded vehicles)** ( $\pm 6$  Mt/yr), innovations that aim to enhance recycling options for waste electronic equipment were pursued in a few earlier SPIRE projects, bringing technologies to TRL5-6. The goal is to separate the metals as much as possible, where hydrometallurgical processes (using aqueous chemistry) could replace pyrometallurgical (thermal) processes. The plan is to deliver three TRL9 projects.

### **SPIRE projects this programme builds on**

**CABRISS** developed a process for PV-panel recycling (with extension to glass and electronic industry) for the recovery of indium, silver and silicon leading to increased competitiveness, full recycling, and recovery of the elements. It is at TRL7; a TRL9 automated dismantling line for 10,000 tonne/yr of PV waste is under development

Once implemented, this technology will reduce GHG emissions by 30%-100% CO<sub>2</sub>e and reduce waste by 99%, eliminating 1.2 Mt/yr end-of-life waste by 2036. The technology will increase the competitiveness of these industries as high benefits are calculated for the recovered indium, silver and silicon.

**CREATOR** develops a process for the extraction of bromine-based flame retardants from plastics especially from the B&C and WEE sector. It is moving to TRL6-7 (20 kg waste/h processing). Extension of the technology to TRL9 (processing 400 kg/hr waste) will need €1.5 million further investment. GHG emissions will be reduced by up to 2.5 MtCO<sub>2</sub>/yr and waste would be reduced by 137 kt/yr.

- **Mineral waste from construction and demolition** ( $\pm 345$  Mt/yr) contains many components, we distinguish the following:
  - **Cement/Concrete:** After crushing concrete, cement, or brick waste into a very fine fractions, it can be cured with CO<sub>2</sub> under high temperature and pressure to produce very strong concrete modules. These technologies are supported by the innovation programme, CO<sub>2</sub> utilisation for concrete recycling (A-7.b).
  - **Ceramics:** Construction demolition waste is crushed and milled prior to its use in ceramics. The LifeCeram project aims to develop tiles that can incorporate waste produced during tile production and other waste from the ceramic sector

<sup>102</sup> In the programming we have assumed that the current TRL is such that the first project needs to bring the TRL to 4-6.

(LifeCeram, 2019). Innovations increase the applicability of waste for recycling into ceramics and aim to improve sorting and separation. Improving sorting and separation can be accomplished by using artificial scanning (such as in glass recycling) and increasing the applicability of waste in ceramics (for example, by removing metals, gypsum which are prejudicial for the process from the other components); current TRL is max 5, the aim is three TRL9 projects.

- **Bricks:** There is a tendency to replace the cement/mortar with organic adhesive (and glue the bricks together), which makes recycling bricks more difficult. However, new processes should be able to separate the glue from the bricks (currently TRL1), enhancing recycling. Taking the expected lifetime of such applications into consideration and knowing that this application has only been applied recently, two TRL9 projects need to be delivered around 2050.
- **Gypsum** is not considered as the gypsum sector is not part of P4Planet.<sup>103</sup>
- **Insulation:** This includes glass wool, which can be recycled when pure and has similar challenges as hybrid materials if it is mixed with components like paper, or chemical (in which case the required innovations are described under chemical recycling).
- **Bitumen:** Can be heated and used again, this is already happening so no specific innovation opportunities have been identified.
- **General:**
  - Roof tiles, marble, slate, concrete, bricks, ceramic tiles, sanitaryware, and glass can be recycled in ceramic products. Wood wastes could be recycled in the manufacture of isolating ceramic bricks or in expanded clays, but technologies are needed to sort them.
  - 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.

The competitiveness of these technologies is not always attractive, so the aim is to deliver two TRL9 projects (starting from the current TRL6-7).

- **Other mineral wastes** ( $\pm 704$  Mt/yr): Currently, 75% of this stream is landfilled. Most of this stream is usually sand—which can already be recycled—gravel, and stones. A big concern from an environmental point of view are contaminants, the focus of this roadmap however is on recycling. Typically, 10%-20% of this stream is a wide scatter of organic components or clay. These can only be recycled by developing processes specifically for the composition of the stream (including the combined separation/conversion of organic components/clay [pyrolysis/gasification]). Innovations can enable bauxite residue to be used as ingredient for (for example, construction) products, and new mechanical/chemical processes can be developed to recover salt, aluminium oxides and aluminium metal from salt slag (European Aluminium, 2016). In the RemovAl project (RemovAl, 2018), the applicability of bauxite residue as a secondary resource is increased by reducing alkali content below 0.5%wt, processing it into a soil stabiliser for civic works applications, thermally treating it into lightweight aggregates and high performance binders or processing it with other industrial by-products in a microwave furnace to produce metallic iron. The aim is to deliver 10 TRL9 projects (assuming that the current TRL of these technologies would be 3). The value of the applications will be relatively low, so it might be difficult to work towards a business case for these applications.
- **Combustion wastes and liquified, stabilised, or vitrified wastes, mineral wastes from waste treatment and stabilised wastes** ( $\pm 118$  and  $\pm 46$  Mt/yr) originate from any thermal and combustion process, incineration and pyrolysis of waste, the mineral fraction from the mechanical treatment of waste and wastes from treatment processes that

<sup>103</sup> When gypsum is part of composites --> refer to composites / hybrid materials.

solidify waste, and stabilise or neutralise dangerous substances by a chemical reaction or vitrify waste in a thermal process.

The volumes generated by these applications may well reduce with:

- The reduced use of fossils, but (new) applications like using biomass in boilers, pyrolysis, and gasification also produce such waste streams.
- Changing from traditional incineration to plasma inertisation would lead to a radical decrease of the volume of wastes<sup>104</sup> and would also increase the possible recycling of these wastes as they could be used in ceramic products (or even in glass ceramics).

Ashes from fuel combustion, sewage sludge, and construction and demolition waste are often used as a secondary resource in the production of cement. Streams are mostly vitrified for downcycling/landfilling, making the resources contained inaccessible.

Unconverted lime from flue gas cleaning applications or slag can be re-carbonated and then used as filler; this CCU process is already described under CO<sub>2</sub> mineralisation. The process resembles natural re-carbonation, but at a much higher speed.

Innovative processes aim to improve washing fly and bottom ashes to recover more soluble salts and to prevent vitrification by reactive separation of metals and minerals. The aim is to deliver seven TRL9 projects (of which five starting at current TRL of 4-5 and two innovative electrochemistry based technologies [starting at TRL3]).

Examples of innovations that could also be pursued include recovery of valuable metals from the following:

- **Basic oxygen converter gas dust** containing up to 15%wt zinc and 50%wt iron: Currently, 12%wt is landfilled; the iron contained cannot be used in the steelmaking process anymore.
- **Dust from the electric arc furnace** (10–30 kg/t of liquid steel) containing up to 50%wt iron: This cannot be reused to produce steel (with the state of the art Waelz process); the share of landfilling is constantly decreasing (now 34%).
- **Composites/hybrid materials** (not separately reported in Eurostat waste statistics): Recycling these streams can be difficult; for example (glass fibre) composites can be used in the cement sector, but trace components (like boron – which delays the settling of concrete) hinder this use of secondary resources. Use of composites/hybrid materials increases, and with that, the need for recycling technologies increases. Constituent materials (natural materials, plastics, metals, and minerals) are well mixed in the material and need to be separated. A CSA will establish which combinations of materials can and cannot be separated (like the metal wheel) and will explore alternatives for the combinations that cannot be separated. New technologies are being developed (currently at TRL3, apart from glass and carbon fibre which are currently at TRL4-5) that allow separation in a different environment, after which the individual streams can be recycled with other technologies (like pyrolysis, gasification; see under “chemical recycling”). The aim is to deliver 10 TRL9 projects.

#### **SPIRE projects this programme builds on**

**ECOBULK** demonstrates and implements a new circular economy model for composite products in automotive, furniture, and building component industrial sectors with among reuse, upgrade, and refurbishment attention to recycling.

**iCAREPLAST** converts nonrecyclable plastics and composites from urban waste into valuable chemicals (alkylaromatic) through chemical routes. The project is moving to TRL6-7 (100 kg plastic/h). Development to TRL9 will require €20 million of investment. The process will reduce

<sup>104</sup> The wastes arising from plasma inertisation are formed by sintered agglomerates instead of fly ashes.

GHG emissions by 45% and will reduce waste by 12% as compared to the benchmark recycling technology. The result will increase competitiveness by more than 200%.

**MULTICYCLE** develops a solvent-based and recycling technology for fossil- and bio-based thermoplastic multilayer packaging and fibre reinforced composites at TRL7 with a potential to continue to TRL9 by 2025.

#### A-10.c.4 Investment needs

Table 29: Investment needs in € million<sup>105</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Collect better data on current recycling and the possibilities to enhance</b>	2020-2024					1x €10	€10
	2024-2030						€0
	2030-2040						€0
	2040-2050						€0
<b>Spent solvents</b>	2020-2024			5x €15			€75
	2024-2030				5x €40		€200
	2030-2040						€0
	2040-2050						€0
<b>Acids, alkaline or saline wastes</b>	2020-2024			5x €15			€75
	2024-2030				5x €40		€200
	2030-2040						€0
	2040-2050						€0
<b>Plastic wastes and Used oils</b>	2020-2024	4*€5	6x €8	4x €15	2x €40		€208
	2024-2030		2x €8	3x €15	4x €40		€221
	2030-2040			1x €15	4x €40		€175
	2040-2050						€0
<b>Chemical and medical waste and sludges and liquid waste from waste treatment</b>	2020-2024	67x €5	6x €8		2x €40		€463
	2024-2030		20x €8	3x €15			€205
	2030-2040			10x €15	13x €40		€670
	2040-2050						€0
<b>Rubber wastes</b>	2020-2024		6x €8				€48
	2024-2030			3x €15			€45
	2030-2040				3x €40		€120
	2040-2050						€0
<b>Health care and biological waste</b>	2020-2024		8x €8				€64
	2024-2030			4x €15			€60
	2030-2040				4x €40		€160
	2040-2050						€0
<b>Metal waste (ferrous, non-ferrous, mixed)</b>	2020-2024	100x €5				1x €10	€510
	2024-2030		30x €8				€240
	2030-2040			15x €15	15x €40		€825
	2040-2050						€0
<b>Wood wastes</b>	2020-2024		18x €8	1x €15			€159
	2024-2030			9x €15	1x €40		€175
	2030-2040				9x €40		€360

<sup>105</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
	2040-2050						€0
<b>Textiles</b>	2020-2024		2x €8	1x €15			€31
	2024-2030			1x €15	1x €40		€55
	2030-2040				1x €40		€40
	2040-2050						€0
<b>Discarded equipment (excluding batteries, accumulators and discarded vehicles)</b>	2020-2024			3x €15			€45
	2024-2030				3x €40		€120
	2030-2040						€0
	2040-2050						€0
<b>Mineral waste from construction and demolition</b>	2020-2024	13x €5	6x €8	2x €15			€143
	2024-2030		4x €8	3x €15	2x €40		€157
	2030-2040			2x €15	3x €40		€150
	2040-2050				2x €40		€80
<b>Other mineral wastes</b>	2020-2024		20x €8				€160
	2024-2030			10x €15			€150
	2030-2040				10x €40		€400
	2040-2050						€0
<b>Combustion wastes and Liquified, stabilised or vitrified wastes, Mineral wastes from waste treatment and stabilised</b>	2020-2024		4x €8	5x €15			€107
	2024-2030			2x €15	5x €40		€230
	2030-2040				2x €40		€80
	2040-2050						€0
<b>Composites / hybrid materials</b>	2020-2024		20x €8	1x €15	1x €40	1*€10	€225
	2024-2030			10x €15	1x €40		€190
	2030-2040				10x €40		€400
	2040-2050						€0
<b>Total</b>		<b>€920</b>	<b>€1,216</b>	<b>€1,545</b>	<b>€4,320</b>	<b>€30</b>	<b>€8,031</b>

#### A-10.c.5 Success factors

- **Consumer awareness and societal acceptance on recycling** must be improved: Consumers need to value products made with recycled materials as much as they do with those manufactured with virgin resources.
- **More efficient waste collection and sorting** is needed to promote increased percentages of secondary resources in products.
- **Waste policies:**
  - Recycling secondary resources requires a thorough evaluation and harmonisation of waste regulations in the EU, including new standards.
  - Removing barriers (for example, regulation when it comes to handling waste streams), including infrastructure for transport, especially cross-border.
  - Create incentives.
- **Open data and resource exchange platforms** that provide transparency on the quality of secondary resources, enabling a **good exchange between the actors in the value chain**.
- **Develop tracking/tracing systems** as an enabler to determine the quality, bio-based/recycled content and the CO<sub>2</sub> footprint of secondary resources. Enhanced traceability enables consumers to make informed decisions based on information on origin and quality.

## Wastewater valorisation

The water industry is increasingly moving from wastewater treatment plants (WWTPs) to wastewater resource recovery facilities (WWRFs) with increasing efficiency by:

- **Recovering valuable nutrients, inorganics, and organics** as much as possible.
- **Eliminating hazardous inorganics and organics** when they cannot be recovered:
  - Convert with reductive processes (such as anaerobic digestion towards energy carriers) in case that is not possible by oxidation.
  - Send to controlled incineration (for example, some sludges of physico-chemical treatment) in case that is not feasible.
  - Send to controlled landfilling.
  - Phase out.
- Extracting as much **energy** as possible.
- **Reusing the water** or **prevent production of wastewater**.
- Using **artificial intelligence and sensing** to manage operations more efficiently, reliably, and remotely.

This could be achieved by cross-sectorial cooperation between the wastewater sector and the urban waste processing companies, which could potentially merge into one.

### Text box 8: Background to the water strategy

The composition of wastewater varies strongly between different industries/plants. Moving towards a bioeconomy may cause an increase of wastewater, thus making adequate treatments, reuse, and recycle indispensable. Alternative water sources and qualities (fresh ground and surface water, rainwater, brackish water, saline water, brines, greywater, black water, recycled water) can be made available and employed for various purposes by users.

The focus of wastewater treatment technologies has always been on cleaning water without too much regard for the value in water. Water's economic and societal value can be created by extracting and valorising substances embedded in used water streams such as nutrients (nitrogen and phosphorous), minerals, chemicals, and metals, as well as energy. This is often done by oxidation, leading to CO<sub>2</sub> emissions.

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). For instance, the total available phosphate in EU sewage streams is estimated at 506,000 tonne/year or 36% of the phosphate currently imported by the EU via mineral fertiliser (van Dijk, Lesschen, & Oenema, 2016). This percentage is significantly higher if a wider scope of wastewater sources are included in the comparison. The EC identified phosphorus as a priority resource for the circular economy (EC, 2014a). Recycling phosphorus reduces the need to mine. If nitrogen is recycled in a similar manner the need for the energy intensive production of ammonia would also decrease.

This focus will be changed to recovering as many valuable components dissolved in the water as possible, only oxidising those components that cannot be valorised. Wastewater treatment will be reimagined by applying separation/recycling steps where possible on concentrated waste streams directly derived from process outputs, thus avoiding a component killing the activated sludge or affecting the treatment process, and 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 a need remains for technologies with broad functionality. The expected increase in of bio-based processes further increases the benefits of these new technologies, as these processes typically generate high amounts of wastewater with high chemical oxygen demand (organic components).

### A-10.c.6 Innovation objectives

The above is reflected in the innovation objectives that follow, enabling **increased/full recycling of wastewater and its components**:

- Separation requires significant amounts of energy (and air/oxygen, in the case of aerobic treatment), so there is an incentive to separate as efficiently as possible. To improve separation technologies the toolbox of cost-effective options that can be used to separate components in wastewater a low eco footprint needs to be expanded (including but not limited to membranes), including primary treatment and modular solutions. There is potential to improve current separation, because:
  - More/new components need to be captured in a different manner. Phosphorus (P), for example is a non-renewable resource that causes pollution when improperly dispersed in the environment. Currently, it is state of the art to capture P producing struvite ( $\text{Mg}(\text{NH}_4)(\text{PO}_4)$ ), a mineral that is already used as fertiliser for a limited range of applications. P is recovered from water at a 50% rate today, but at high costs and often insoluble forms that makes it inapt for reuse in agriculture. Therefore, alternative innovative technologies (TRL5) are needed to recover higher rates of P, N, K, and Mg in proper form for application in fertilisers.
  - Cost-effective efficiency needs to be increased. A purge (losing water and components) is often needed to avoid accumulation of trace components. Innovative technologies are required that combine the conversion of components in wastewater to value-added chemicals with their accumulation for effective harvesting.
  - There is potential to reduce energy consumption. For example, the energy requirements for aeration can be reduced significantly by using oxygen (available as side-product from the new local production of green hydrogen) rather than air.
  - Separation is often organised at a cluster level. Treating locally (directly at the output of a plant, before diluting with other streams) should be pursued where possible. Significantly cheaper, smaller scale modular treatment systems for decentralised (primary) treatments will need to be developed.
  - Achieving a high yield extraction, even at **very low concentrations** is important not only for the water treatment itself, but also for the re-use and valorisation of chemicals and biomolecules.
- **Increase valorisation of solutes from wastewater treatment.** Innovative conversion technologies need to be developed that can valorise solubilised compounds to valuable chemicals, e.g. microbial production by fermentation or microbial conversion to polymers. Recyclable materials 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 solutes recovered from wastewater by 2025 and 90% by 2050. This includes modular solutions.
- **Increase valorisation of solids from wastewater treatment 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/components (e.g. magnesium, calcium, precious metals). The aim is to recycle 50% of the unused (in)organic solids by 2030 and to strive towards 100% by 2050, eliminating landfilling and reducing feedstock cost with cost-effective production processes from waste streams. This includes modular solutions.
- Optimise **recovery of the energy value in wastewater** for which new, affordable technology needs to be developed, such as:

- Co-digestion of the organic fraction of municipal waste to improve the organic load and gas production.
- Technologies that use biogas with increased efficiency.
- Systems accumulating low temperature heat for industrial processes or public services purposes.
- Reductive processes (like anaerobic digestion) that generate energy sources used to make the water treatment energy neutral, or to provide energy to other industries. This should be part of a systemic approach, taking all components and their value into account. Such an approach requires the identification and quantification of all energy balance components, options to reduce energy consumption, increased energy recovery, and use of renewable energy.
- Develop **alternative processes with reduced water use**, this is especially relevant for the increasing application of bio-based processes where fermentation processes are completed in water solutions. Alternative processes, such as solid-state fermentation, can increase yields to produce chemicals without presence of free water, and electrification can replace steam heating.
- **Develop optimised wastewater treatment for freshwater substitution** to allow full recycling of wastewater. This reduces the uptake of freshwater, which is expected to become increasingly scarce in Europe with summer water shortages; the aim is to apply new technologies that enable a 40% acquisition of freshwater from the wastewater treatment plant in 2030 and 100% in 2050. This includes modular solutions.
- **Improve sensors and monitoring** of water quality to affordably control water quality (avoid efforts to purify already clean water and to enable the other innovation objectives). This includes detection methods in complex media and prediction of ecological and toxic effects. Sensors must be cheaper. Fast (semi) automatic decision-making that results in capability and quality is needed. Fast, reliable, and intelligent prediction and decision support systems are also needed, based on the analysis of big data, the magnitude of which is increasing exponentially. This requires the combined utilisation of advanced technologies and algorithms. Signal processing, computer vision, machine learning, software engineering, knowledge-based systems, data mining, and artificial intelligence are progressively used to manage data and allow the use of automatic or partially automatic digital support systems respond to changes in a timely manner.
- Failures (like leakages) reduce the (energy) efficiency of the water treatment. To prevent failures, and to timely adjust operations to changes in the water composition and to limit the duration of failures, robotics need to be developed that provide inspection and maintenance duties in water systems. Virtual reality (which enables walking through the 3D water treatment plant from the office) allows maintenance without interrupting the process, even in cases of highly pressurised pipes with hazardous chemicals.

The last two innovation objectives apply to all process industry. The other innovation objectives act on the interface between the process industry and the wastewater sectors. The innovation objectives are all fully cross-sectorial.

### **A-10.c.7 Impacts**

#### ***Greenhouse gas emissions***

EU sewerage waste management and remediation activities consumed 70 PJ of electricity annually in 2016 (according to (Eurostat, 2019b)), leading to 5.7 MtCO<sub>2</sub> emissions. New technologies should cause no or low GHG emissions. Electricity consumption can be reduced by:

- Increasing the efficiency of water management/treatment.
- Using renewable electricity where feasible.
- Eliminating still relevant water losses (which vary widely among different member states; in some countries the percent value of water loss exceeds 20%).

Some technologies can generate renewable energy sources that can displace fossil fuels (for example biogas from anaerobic digestion replacing natural gas in the process industries).

## **Waste**

More than 40 billion m<sup>3</sup>/year of wastewater is treated in the EU, of which only 964 million m<sup>3</sup>/year is reused (EC, 2017). Four types of disposal make up a considerable share of the total volume of sewage sludge treated, varying significantly over the various member states (Eurostat, 2014):

- At least half of the total was used as fertiliser for agricultural use in two EU member states, Ireland (79%) and Lithuania (51%).
- By contrast, 84% of sewage sludge was composted in Estonia (2016 data) and 53% in Luxembourg.
- Alternative forms of sewage disposal may be used to reduce or eliminate the spread of pollutants on agricultural or gardening land; these include incineration and landfill:
  - As there are more environmental concerns about the latter, incineration is increasingly the method of choice. The Netherlands (98%), Germany (64%), Belgium (79%), and Austria (53%) reported incineration as their principal form of treatment for disposal.
  - Discharge in controlled landfills was practised as the principal type of treatment in Malta (100%), Romania (59%), and Croatia (57%).

Based on incomplete data<sup>106</sup> for 2016 (Eurostat, 2020a), the generation/disposal of waste from wastewater treatment plants is at least 7 Mt/year in the EU, with large differences between member states. Around 10% of this waste is currently landfilled and around 20%-40% is currently incinerated. The amount of landfilled/incinerated sludge could be (significantly) reduced if more components are valorised.

Additionally, the reuse of water reduces the water abstraction from natural sources. As industry accounts for about 40% of water abstraction in the EU, this will have a significant impact.

## **Competitiveness**

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

- Valorisation of secondary resources reduces virgin material- and energy-needs, thus cost.
- Reusing discharged materials increases Europe's resource independence; the phosphates example illustrates that the import dependency of the European fertiliser industry can be reduced significantly (currently phosphates are imported mainly from Russia and Morocco).
- Full recycling of wastewater would lead to high costs, which innovations should bring down.

Without innovations, achieving near zero water discharge could be costly, but it is needed in places with limited availability of freshwater. Valorising components in the water can be competitive in specific cases.

## **A-10.c.8 Programming**

**SPIRE projects this programme builds on**

<sup>106</sup> 23 member states submitted a >0 data point for sludge from urban wastewater treatment plants, and 7 did so for sludge from other wastewater treatment plants

**PORTABLECRAC** bring a cost-effective regeneration method for activated carbon, used in water treatment, with 86% costs reduction and 4 times less CO<sub>2</sub> emissions compared to the state-of-the-art technology.

**ReWaCEM** developed improved technologies for energy and water footprint reduction by 30%-90% with simultaneous metal resource recovery in metal plating, galvanising, and printed circuit board industry. Development reached TRL6-7.

The following activities are expected:

- **Improve separation technologies:**
  - Apply an integrated treatment of complex industrial wastewaters by membrane technology (TRL4-6).
  - Production of large quantities of membrane and modules (TRL6-8), which reduces the production costs through economy of scale and scales-up and integrates modules in large systems; focus on chemical free membrane operation and relation to pumping costs (Water Europe, 2017).
  - Intensified water purification/filtration concepts (TRL3-5) 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 (TRL4-6) (Water Europe, 2017).
  - Generate new treatment technologies, e.g. hybrid membrane systems (TRL3-5), for water treatment increasing synergy between membrane systems and (granular) activated sludge systems, oxidation, adsorption, and coating. Improvement of advanced oxidation and adsorption/absorption technologies (TRL5-7) (e.g. active carbon, ozonation) (Water Europe, 2017).
- **Increase valorisation of solutes from wastewater treatments:**
  - Include innovative biological nutrient (nitrogen, phosphorous) removal processes for energy efficient treatments and nutrient recovery (TRL4-6).
  - Valorisation of industrial wastewater (TRL6-7) (Water Europe, 2017). This could lead to substantial volumes of valuable elements, such as P, salts, minerals, nutrients, acids, and alkalis becoming available.
  - Integration of electrochemical technologies for industrial waste valorisation: electrodialysis (mono and bipolar technologies metathesis) and recovery of chemicals (acids and alkalis); development of low cost technologies for efficient separation of interferences (Water Europe, 2017).<sup>107</sup>
  - Biological phosphorous accumulation with agricultural application potential (TRL4-6).
  - Biochemical engineering technologies that apply fermentation technology to convert toxic phenols by microbial cells for intracellular product accumulation (microbial oil for e.g. biodiesel production, or polyhydroxyalkanoates bioplastics) and its recuperation from wastewater flow systems (current TRL2-3).
  - Brine management requires disruptive innovation to become competitive.

#### **SPIRE projects this programme builds on**

**ZERO-BRINE** applies an integrated treatment of complex industrial wastewater by 14 different membrane technologies (TRL4-6). It has four operational pilot plants to concentrate brines from wastewater at TRL6-7. For salts recovery, development toward TRL9 is expected by 2022 with an extra cost of €5-€10 million. Recovery of other compounds still starts at TRL4.

- **Increase valorisation of solids from wastewater treatments into new materials or recovery for energy production:**

<sup>107</sup> For the determination of the investment costs (next paragraph) we have assumed the first projects needed are TRL4-6 projects.

- The valorisation of cellulose toilet paper residues in the wastewater by sieving out cellulose fibres (TRL4-6) or by their fermentative conversion to bioethanol.
- Recovery of biopolymers (alginates, proteins, etc.) as value-added products by extraction from granular sludge (TRL4-6).
- Development of highly effective photocatalytic technologies for controlled conversion of micro-pollutants (emerging pollutants) to desired products instead of unknown degradation products (TRL1-2).
- Recovery of biopolymers (alginates, proteins, etc.) as value-added products by extraction from granular sludge (TRL4-6).
- Development of highly effective photocatalytic technologies for controlled conversion of micro-pollutants (emerging pollutants) to desired products instead of unknown degradation products (TRL1-2).
- Sludge contains many fine non-ferrous metals particles that are difficult to dry. Innovative processes capable of treating these sludges must be flexible and capable of handling different types of waste streams that include different steps (such as 150 Mt/year bauxite residue/year and 45 Mt/year of basic oxygen furnace sludge – currently landfilled), 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) and quartz fines from mining and from the silicon industry. This technology could also be applied to oily mill sludges from the steel industry (currently at TRL 8).
  - Flotation<sup>108</sup>.
  - Agglomeration through pelletisation, extrusion, or briquetting to make finely granulated solid resources suitable for pyrometallurgical treatments (currently at TRL 6-7).
  - Pyro- and hydro-metallurgical treatments (currently at TRL 5-6).
- **Optimize recovery of the energy value in wastewater:**
  - Develop optimal cascading of water streams and optimise the energy content (temperature) of the water streams, including increasing energy production from water sources (TRL6-8) or energy recovery in water flows through efficient turbine technologies (Water Europe, 2017).
  - Where (pre-)concentration of salts is often a key step for the effective removal. The electrodialysis technology can also be used to recover energy from concentrate salt streams (blue energy).<sup>109</sup>
- **Develop optimised wastewater treatment for freshwater substitution** using the optimal combination of chemical and biological treatment methods, with general application of smart aerated granular sludge (AGS) (TRL7-9) integrated with physical and chemical technologies (e.g. membranes, biopolymer extraction). This integration leads to significant improvements in treatment intensity, energy consumption, and land use and resource efficiency. The approach should:
  - 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.

## SPIRE projects this programme builds on

<sup>108</sup> For the determination of the investment costs (next paragraph) we have assumed the first project needed is a TRL4-6 project.

<sup>109</sup> For the determination of the investment costs (next paragraph) we have assumed the first project needed is a TRL9 project.

**INSPIRE WATER** developed process water recycling systems and demo's to TRL7 with the aim to go for a demo case at TRL9 in 2024. The high water recycle leads to less desalination energy consumption in the specific cases.

**SPOTVIEW** can already reduce freshwater intake for pulp and paper by 20%-50%, for the steel industry by 80%-90% (freshwater substitution by backwash water and river water after CDI), for dairy by 25%. Energy was produced through biogas production. This can be upgraded from TRL7 to TRL9 by 2025, leading to more than 10% GHG reduction and 25%-50% wastewater discharge reduction.

- **Develop alternative processes with reduced water use:**
  - Increasing efficiency of cooling water systems (TRL7-8), reducing the use of cooling water and its impact on water systems.
  - Solid state fermentation processes with the absence of free water (instead of the current submerged in water fermentation processes) where new production processes (new products) (TRL2-3) and new technology for improved humidification and heat exchange (TRL5-6) have to be developed, and the labour intensity of the processes needs to be reduced.
  - Develop processes that tolerate secondary water.<sup>110</sup>
- **Improve sensors and monitoring:**
  - Use a strong multidisciplinary approach using integrated real-time (bio)process control and monitoring (TRL4-6).
  - Make use of artificial intelligence for smart process control (TRL1-3).
  - Automate monitoring in water networks, energy/heat harvesting and reuse from water, optimisation of water use in cooling/heating in process industries (TRL6-8).
  - New, cheaper sensors for detection and chemical measurement of pollutants (TRL approximately 5, 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.<sup>111</sup>
  - Demand forecasting for efficient network, buffer, and pumping management (TRL6-8).

The list above contributes to water recycle/reuse processes and loops with continuous water quality control, process feedback loops, and process control.

- **Develop robotics:**
  - Develop a multi-sensing inspection robot for pressurised water pipes that can enter through small access points and identify defects (current TRL4-5).
  - Develop a robot able to perform repair/maintenance tasks in different environments when a defect is detected (current TRL6-8).
  - Create a robot for safe and rapid access and repair of underground pipes (including pavement cutting, detection of underground networks) (current TRL6-8).
  - Develop a multi-sensing inspection robot for water and wastewater pipes that is able to perform continuous measurements, detect water contamination issues, trigger alerts, and grab samplings if needed (current TRL7-9).
  - Develop autonomous surface vehicles that can control and communicate water quality and can operate long-term without human intervention (current TRL6-9).

The expected activities would benefit from the development of new, better catalysts, as described in the innovation programme, Next-gen catalysis (A-9.a).

<sup>110</sup> For the determination of the investment costs (next paragraph) we have assumed the first projects needed are TRL3 projects.

<sup>111</sup> For the determination of the investment costs (next paragraph) we have assumed the first projects needed are TRL4-6 projects.

## A-10.c.9 Investment needs

Table 30: Investment needs in € million<sup>112</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Improve separation technologies	2020-2024		8x €5	1x €10			€50
	2024-2030			4x €10	1x €25		€65
	2030-2040				4x €25		€100
	2040-2050						€0
Increase valorisation of solutes from wastewater treatment	2020-2024	13x €1.5	7x €2.5	2x €5	2x €25		€97
	2024-2030		4x €2.5	5x €5	1x €25		€60
	2030-2040			2x €5	4x €25		€110
	2040-2050				2x €25		€50
Increase valorisation of solids from wastewater treatments into new materials or reuse for energy production	2020-2024	25x €1.5	10x €2.5	2x €10	1x €25		€107.5
	2024-2030		6x €2.5	6x €10	3x €25		€150
	2030-2040			2x €10	5x €25		€145
	2040-2050						€0
Optimize recovery of the energy value in wastewater	2020-2024				2x €25		€150
	2024-2030						€0
	2030-2040						€0
	2040-2050						€0
Develop optimised wastewater treatment for freshwater substitution	2020-2024	12x €1.5			1x €25		€43
	2024-2030		6x €2.5	2x €5	1x €25		€50
	2030-2040			2x €5	1x €25		€35
	2040-2050						€0
Develop alternative processes with reduced water use	2020-2024	17x €1.5	4x €2.5		1x €25		€60.5
	2024-2030		4x €2.5	2x €5			€20
	2030-2040			2x €5	2x €25		€60
	2040-2050				1x €25		€25
Improve sensors and monitoring	2020-2024	12x€1.5	8x €5		2x €25		€68
	2024-2030		2x €5	3x €10			€40
	2030-2040			1x €10	3x €25		€85
	2040-2050				1x €25		€25
Develop robotics	2020-2024		12x €5	4x €10	2x €25		€150
	2024-2030			2x €10	2x €25		€70
	2030-2040				1x €25		€25
	2040-2050						€0
<b>Total</b>		<b>€118.5</b>	<b>€252.5</b>	<b>€335</b>	<b>€1,035</b>	<b>€0</b>	<b>€1,741</b>

## A-10.c.10 Success factors

- Municipalities investing in new water treatment plants to recover valuable, recyclable materials.
- Industries applying innovative and smart integrated technologies (granular sludge, membranes) to treat and reuse wastewater efficiently.

<sup>112</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-11 Industrial-urban symbiosis

### A-11.a Demonstration of industrial-urban symbiosis

#### **SPIRE projects this programme builds on**

**BAMB** is redesigning buildings to bank valuable materials rather than simply contributing to waste at end-of-life. The resulting circular economy value chains is based on Materials Passports and will reduce GHG emissions by 40% and waste by 75%-90% upon implementation at TRL9 by 2024, given further investment of €9 million. Competitiveness will be strengthened and supported through standardisation. A big hurdle is the lack of traceability of the materials.

#### **A-11.a.1 Innovation objectives**

The goal of this innovation programme is to realise demonstration projects for industrial-urban symbiosis (I-US). Projects should be developed that identify, combine, and integrate multiple technologies or business models to demonstrate I-US. The I-US demonstration projects can be focused on water, energy (a.o. heat), or resources (both urban and industrial flows) and gases.

#### **A-11.a.2 Impacts**

For the assumptions and methodology underlying our impact estimations reference Appendix E .

##### ***Greenhouse gas emissions***

GHG savings are achieved by increased I-US and closing loops. This is mainly due to the reduction of primary resource consumption (as secondary resources displace primary resources) and the reduction of energy demand.

According to Klaus Sommer's recent report, the available data are insufficient to make a reliable prediction about the GHG impact of industrial symbiosis. However, it also states that an impact in the order of 10% is plausible (Sommer, 2020). Assuming this 10% impact, the GHG impact would be around 50 MtCO<sub>2</sub> for all P4Planet sectors.

The impact will be limited to the 12 TRL9 demonstrations in 2030. Assuming they collectively cover 1% of the potential, the impact is about 0.5 MtCO<sub>2</sub> in 2030.

##### ***Waste***

Studies have shown that there is considerable value in industrial symbiosis. Market analysis shows potential of €72.7 billion through landfill costs avoidance alone (Trinomics, 2018). The total waste reduction volume is not provided, and it is also unclear how this number relates to the roughly estimated waste reduction potential.

The SHAREBOX project analysed the expected sustainability impacts and benefits of using SHAREBOX's ICT platform to facilitate 11 synergies. A waste reduction of 27% is expected. This 27% can be achieved with available technologies, and would drastically reduce the remaining waste (which needs to be addressed with new technologies). This 27%, if applied to the total EU landfill volume within the P4Planet scope<sup>113</sup> of 1.4 Gt, implies a waste reduction of about 380 Mt in 2050.

The impact will be limited to the impact of the 12 TRL9 demonstrations in 2030. Assuming the demonstrations collectively cover 1% of the potential, the impact is about 2 Mt in 2030. Fresh water savings of up to 40% can be achieved in industrial water networks, according to an EPOS analysis (EPOS, 2019).

<sup>113</sup> See Appendix E-2 for the specification of the scope. Note that here landfilled waste is used from Eurostat and not generated waste like in Appendix E-2.

## Competitiveness

The synergies created by closing loops lie in reduced waste management costs and the value created by selling these waste flows as secondary resources. The Trinomics study estimated the market value of €72.7 billion through landfill costs avoidance alone, and between €6.9 billion and €12.9 billion in transactions of secondary resources (Trinomics, 2018). This estimation is expected to be an overestimation considering that landfill costs for municipal waste are used (which are typically higher than for construction and demolition waste, which covers a large part of the potential), and considering that member states are benchmarked to other member states, not taking practical limitations into account.<sup>114</sup> The number shows that there is considerable value in the symbiosis.

Closing loops results in less reliance on primary resources and less associated supply chain risks, and the H4C result in increased innovation and cooperation that will also create value for various regional stakeholders.

### A-11.a.3 Programming

To realise I-US, business development opportunities must be identified, then multiple technologies need to be combined and integrated for the implementation. This can be downstream processes, recycling, digital technologies, logistics, etc. It will also be crucial to overcome multiple non-technological barriers, such as access to data without compromising the compliance regulations, access to resources and infrastructure, fair and transparent distribution of gains, regulatory aspects, trust and legal security for long-term mutual dependencies.

### A-11.a.4 I-US needs to be demonstrated in various applications and regions. Each region will work with a project portfolio tailored to their specific potentials and requirements. TRL7-8 projects will be done in multiple regions until 2030; 18 before 2024 and 18 after 2024. TRL9 Investment needs

Project costs for TRL9 can be in the range of €10-€25 million, and for this estimation we use the average of that range: €18 million. For TRL7-8 projects, the investments are expected to be half of the TRL9 investments: €9 million.

Table 31: Investment needs in € million<sup>115</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Demonstration of industrial-urban symbiosis	2020-2024			18x €9			€162
	2024-2030			18x €9	12x €18		€378
	2030-2040				6x €18		€108
	2040-2050						€0
<b>Total</b>		€0	€0	€324	€324	€0	€648

### A-11.a.5 Success factors

- Waste policies: Remove barriers (for example regulation when it comes to handling waste streams) and create incentives. Waste should for example be recognized as a resource to remove barriers, including transport infrastructure, especially cross-border.
  - facilitation and a number of coordination tools to help overcome existing barriers to symbiosis
- Access to secondary resources (which will be a competitive issue).

<sup>114</sup> Notably, the potential for recycling mineral waste in Sweden is questionable considering the low local demand for these minerals.

<sup>115</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

- MSW collection is a first prerequisite for the availability of waste streams. Sufficient volume should be available and adequate separation and sorting is needed to deliver the right quality of the streams.
- Technologies from other innovation programmes: This includes recycling technologies (innovation programmes Upgrading secondary resources in A-10.c and Wastewater valorisation in 0). Other technologies could include CO<sub>2</sub> capture technology (innovation programme Flexible CO<sub>2</sub> capture and purification technologies in A-6.a), membranes for separation (innovation programme “Electrically driven separation in A-4.b), or digital technologies that enable faster and more efficient engineering optimisation (innovation programme Digital process development and engineering in A-13.b).
- True pricing mechanisms made possible by digitalisation are essential to close the gap with non-sustainable technologies or production (innovation programme “Digitalisation of industrial-urban symbiosis” in A-13.f).
- Legal possibility to valorise waste streams and legal framework for negotiation of contracts: Policies and regulations can in be a barrier to implementation of I-US projects. These barriers should be removed on a European, member state, and local level.
- Many breakthroughs will undoubtedly be made in exploring new, economically feasible designs for production modules that are smaller in size, less capital intensive and more agile. Meanwhile, increasingly interdependent and connected cross-sectoral systems will require a digital infrastructure and intelligent solutions that are resilient to cyberattacks and other disturbances.

A-12.b

## A-12 Circular regions

Section 3.4 presents H4C and describes the need for support to promote the emergence of multiple H4C. The two innovation programmes in this innovation area work together to deliver this.

**On a regional level, knowledge on** local availability of material and heat flows and resulting opportunities and requirements need to be systematically processed. Value chains need to be developed based on them, taking preferably into consideration the optimization of logistics. d stakeholders and create regional value loops in an inter-plant scenario.

**On the European level,** apart from the development of the technologies, knowledge and best-practice exchange is needed. This will be provided by the European Community of Practice that will bring together the regional H4C in one network of networks (see Figure 10).

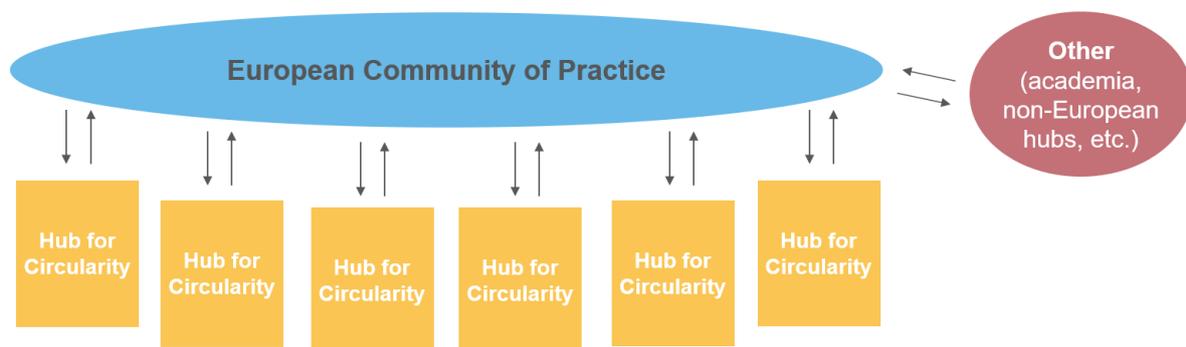


Figure 10: European Community of Practice connecting and actively sharing practices and knowledge between Hubs for Circularity

### Impacts

H4C and the European Community of Practice will help accelerate and coordinate the rollout of I-US. The innovation programmes contribute to the impacts that are specified under the innovation

programme Demonstration of industrial-urban symbiosis (A-11.a). It is unlikely that the impacts of that programme can be achieved without the two innovation programmes in this section.

## A-12.a European Community of Practice

While the implementation of I-US and closing circularity loops are in their infancy, they are not new concepts. Many initiatives and publicly funded projects have existed on various levels, from European-scale to national and regional projects. Many tools, models, and technologies have been developed in completed or running projects, which in some cases are insufficiently visible or accessible for managers of symbiosis, after the projects are finished. The value for specific I-US cases is frequently not known well enough, existing gaps lack clarity, there is a need of more awareness building and uptake, after the initial projects.

There is a need for the evaluation, systematic characterisation, constant update, and provision of symbiosis and circularity-related solutions. There is also a need to connect the regional H4C and to ensure that they mutually profit from the knowledge and experience exchange.

### **SPIRE projects this programme builds on**

**FISSAC** developed an innovative industrial symbiosis model for a zero-waste approach in the resource intensive industries. In addition to guidelines and training, the model led to blended cement and eco tiles at TRL6 leading to 35%-40% GHG reduction and 25%-30% reduction of waste.

**HARMONI** brings relevant stakeholders of the process industry together to jointly identify, analyse, and propose solutions for the regulatory bottlenecks and standardisation that hamper innovation.

**SCALER** aims to increase the uptake of industrial symbiosis in Europe by producing a set of best practices, guidelines, and business systems.

### **A-12.a.1 Innovation objectives**

The programme's aim is to:

1. Build the European Community of Practice that connects H4C on the level of knowledge management and services
2. Synthesise findings into generic learning/frameworks and keep knowledge about state-of-the-art solutions updated
3. Enable evaluation of I-US projects
4. Facilitate education

### **A-12.a.2 Programming**

To lead the development of the European Community of Practice, a team of people with related technical expertise and backgrounds in stakeholder management and regions will build, maintain, and manage the network, initiatives, and knowledge base. The associated costs are estimated at €0.5 million annually. This team will coordinate the following activities:

- All project results will be screened for relevant technologies, business models, IT platforms, decision-support tools, and possible organisational, legal, and societal change concepts. Results will be evaluated by applicability for specific implementation cases and to indicate gaps and weaknesses. The evaluation work should incorporate the results of Klaus Sommer's report. The work will enhance the transferability of tools and technologies from one application to another, wherever possible.
- A framework will be developed for the evaluation of material flows and as a basis for identifying the potentials for I-US. Costs are estimated to be €2 million for a 3-year project. The framework's functionality should be evaluated in 2024 and updated accordingly. This must be done by independent experts. Costs are estimated to be €0.5 million.

- The European industry and municipalities will be systematically screened for major resource flows with potential of entering symbiosis, mapped, and evaluated on expected impact and boundary conditions for the implementation of symbiosis (such as the need for new infrastructures or change of regulations). This should build on, and bring together, the available public data (for example the E-PRTR database, country databases, permit registries, and data from existing initiatives) and the waste mapping study that is programmed in innovation programme, Upgrading secondary resources (see A-10.c).
- The European Community of Practice will use the study's results to develop or document cross-sectorial symbiosis evaluation tools and governance models for the operation of a H4C that could be of help for further emerging Hubs. This will include issues such as anti-trust limitations, intellectual property, transparency, mutual long-term dependencies, and the proper calculation and redistribution of gains between symbiosis partners. Governance models will aim to coordinate municipal and industry planning. For example, 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. The governance models will include business-to-territory models for the provision and operation of connecting infrastructures, for the logistics of the resource flows for recycling (tracking, collection, transport), and for shared procurement and services (e.g. maintenance, security, training).
- The European Community of Practice also addresses important non-technological aspects, most notably mapping the effective framework conditions and facilitating the sharing of tools between regions.
- The European Community of Practice will engage with other stakeholders (e.g. local universities or other education institutions) to facilitate the training of circular practitioners and contribute to the definition of new profile requirements due to changing jobs, where necessary. These practitioners should have an in-depth understanding of the potentials and challenges of industrial and urban symbiosis, the state-of-the-art tools and databases, and newest business models.
- To keep information updated, the European Community of Practice will connect to existing activities on circularity and all running relevant projects from other innovation programmes to evaluate and include the results in their database and tools and frameworks. The funded projects under P4Planet will be required to provide information in collaboration.
- With the H4C, the European Community of Practice needs to track regional needs regarding I-US so they can tailor the information to serve the needs. H4C will be required to rate the services of the European Community of Practice to assess whether the services are useful and to what extent. If useful, the European Community of Practice will also connect similar H4Cs to enhance sharing of best practices (twin hubs). An IT living platform could be beneficial, preferably based on the platforms designed in projects. This will aggregate the data and make it accessible for the H4C. This data aggregation will allow for constant updating. 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 European Community of Practice should be evaluated in a CSA. In this evaluation, the business value generated by the European 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.
- In the evaluation, setting up a trusted EU hosted cloud for data transfer across companies and sectors, or a data marketplace for industrial data, should be considered.

### A-12.a.3 Investment needs

We assumed that the evaluation in 2024 is positive.

Table 32: Investment needs in € million<sup>116</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>European Community of Practice team</b>	2020-2024	Technology investments are included in the other innovation programs				4x €0.5	€2
	2024-2030					6x €0.5	€3
	2030-2040					10x €0.5	€5
	2040-2050					10x €0.5	€5
<b>Enable prioritisation of I-US projects</b>	2020-2024					€2	€2
	2024-2030					€0.5	€0.5
	2030-2040						
	2040-2050						
<b>Collecting knowledge and tools etc. and making this accessible</b>	2020-2024					€1	€1
	2024-2030						
	2030-2040						
	2040-2050						
<b>Knowledge sharing platform</b>	2020-2024					€1 + €0.5	€1.5
	2024-2030						
	2030-2040						
	2040-2050						
<b>Total</b>		€0	€0	€0	€0	€20	€20

### A-12.a.4 Success factors

- H4C sharing its experiences and knowledge with the European Community of Practice
- P4Planet projects sharing learnings and detailed project information

<sup>116</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-12.b Development of Hubs for Circularity

Section 3.4 presents H4C and describes the need for support to promote the emergence of more H4C. Through this innovation programme, the establishment and development of H4C is stimulated.

This programme is about enhancing and facilitating the practical implementation of climate neutrality and circularity in regions, embracing clusters of process industry and municipal infrastructures (including energy infrastructure), and 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 resources.

A range of relevant technologies are still being developed (mostly in parallel innovation programmes within this P4Planet roadmap). Even if in short term there are no technological gaps, still their implementation is hampered by numerous non-technological barriers. Therefore, the readiness level of I-US can be measured in terms of the availability of technology (i.e. TRL) but also in terms of the managerial, social and economic readiness for implementation. A holistic approach is required.

Regional framework conditions vary depending on the presence of specific industries and stakeholders, the corresponding availability of current and future resource flows, the (un)availability of infrastructures, and specific legal or financial constraints related to them. Some of the regional challenges are universal and can be tackled on the European level (e.g. international infrastructure development research and technology development, etc.), whereas many of them are region-specific and case-related and can only be dealt with when approached individually within a region, addressing the specific needs and engaging with regional stakeholders.

The results of P4Planet projects related to industrial symbiosis and of discussions with pioneering symbiosis regions imply that bridging the Valley of Death for I-US requires the brokerage and support 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 H4C becomes relevant.

H4C should be established in regions with the following characteristics:

1. A set of specific needs and opportunities related to economic and environmental transition. These can be goals on circularity (near zero landfill waste and water discharge), climate (CO<sub>2</sub> 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 with the goal of becoming a zero-waste region or a climate neutral region by 2030, 2040, or 2050, depending on their point of departure. The frontrunners should move further, and the followers can catch up or become a leader in a new niche (e.g. in some new areas of recycling).
2. The concentration of process industry is a key enabler to reintroduce bulk amounts of resources in the industrial process. Cooperation with other industries is still desired (waste management industries, energy plants, and water utilities).
3. 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.

### A-12.b.1 Innovation objectives

The objective of this innovation programme is to contribute to the realisation of I-US and GHG emissions reductions by supporting the development of H4C. The needs likely differ regionally. The support required depends on the existing regional structures:

- H4C developed from scratch can be necessary for regions where no structures exist so far. Setting it up may require a dedicated team of 2-3 people to coordinate between

stakeholders and assess I-US opportunities. Emerging hubs can be connected to similar H4Cs (twin hubs).

- Collaborative stakeholders' support can be an add-on. For example, an additional team member in existing team can connect and align with the European Community of Practice, using the learnings and identifying opportunities from to help implement I-US in the H4C.

The H4C will connect to existing and emerging structures, where relevant. For example, territory hydrogen sites for hydrogen or living labs for water.

### A-12.b.2 Programming

The programme is expected to accomplish the following:

- **Until 2030:** To deliver the 15 lighthouse H4Cs in 2030, up to 20 H4C are to be funded in Europe (to account for the risk that some H4Cs might not develop as fast as others)
- **2030-2040:** To deliver the 20 lighthouse H4Cs in 2030, up to 25 H4C are to be funded
- **2040-2050:** To deliver the 10 lighthouse H4Cs in 2030, up to 17 H4C are to be funded

P4Planet will provide seed funding for facilitators, and support projects that further the H4C.

Pre-conditions for implementation include the following:

- *Support and commitment of stakeholders* in the region (only one H4C in the region for an area, no doubling or overlaps). Support will manifest in combined financing schemes for H4Cs with contribution from the industry and from regional authorities. For an emerging H4C this can be through letters of intent.
- *Business-to-territory (B2T) plan* for the sustainability of the H4C in the region. How will the H4C secure its own existence and financing after the period of public funding to continue finding opportunities for symbiosis and GHG emissions reductions.
- *Co-investment framework* includes funding by the regional authorities or other needed instruments (e.g. infrastructure and industrial infrastructure funding) and industrial or other private investments.
- *Regional goals and intentions* by the regional authorities (can be a municipality or a port authority).
- *Participation in the European Community of Practice.* This can be through sharing experiences, best practices, tools and frameworks, participating in conferences, guiding other H4Cs.

The incubation or development of H4Cs should be supported with an EC contribution of up to €1.5 million each for 2 years each. The use of the funds will follow the individual B2T plan and co-investment plan. The funds can be for personnel costs or for any knowledge-intensive or data-intensive services, whatever is most necessary or suitable to attain justified impactful results in the specific region and to create transferrable knowledge.

Besides seed funding, more mature H4Cs can have **specific funding needs** related to their development. Possible actions that could stimulate the development of H4C include the following:

- Establish management and brokerage structures or develop existing structures to incubate the H4C. Such structures need to be individual to best address the needs and peculiarities of the regions.
- Specific generic and region-specific non-technological (cross border, international) barriers to implementation (policies, stakeholders, and their interests).
- Mitigate these barriers: the options and their prospects, acceptance finding, implementation plans, and execution trajectories, cross-border synchronisation.
- Connect local stakeholders (process industries, other sectors, public sector, civil society and finance) within the regions and across regions.

- Analyse the specific resource flows, strengths, and weaknesses, develop business cases and models for their use for symbiosis and advocate for the application with the relevant regional stakeholders. This includes the optimisation of logistics and optimal scale of installations.
- Based on the analysis mentioned above, develop a regional business strategy towards symbiosis and circularity that includes CO<sub>2</sub> abatement and climate neutrality goals.
- Use available tools and develop collaboration projects that address closing the gaps for symbiosis launch (depending on the potential implementation cases). Both should focus on technologies and on dealing with non-technological barriers aimed at de-risking investments.
- Find and activate financial means for the implementation, including complementary funding instruments on all levels.
- Collaborate extensively with industries to foster the implementation of cases and demonstration projects.
- Network with EU-wide community of practice to exchange best practices.
- Disseminate 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.

Such activities can be supported through P4Planet based on the needs of the H4C. Based on the analysis of the regional potential and of arising new value chains, it can be found out that collocation of specific companies might appear to be advantageous and needs to be supported to complete value chains. Such companies could be potential takers of resources or side flow takers, or solution providers for symbiosis or circularity sites. There is a high potential for start-ups and SMEs.

The support for specific funding needs is expected to cost on average €0.5 million per activity. It increases as the number of H4Cs in Europe increases.

### A-12.b.3 Investment needs

The investments needed to support the H4C are depicted in the table that follows. Note that this does not include the funding for innovation projects. These are funded from the other innovation programmes and through co-investments.

Table 33: Investment needs in € million<sup>117</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
<b>Incubation/ development of Hubs</b>	2020-2024	Technology investments are included in the other innovation programs				10x €1.5	€15
	2024-2030					10x €1.5	€15
	2030-2040					25x €1.5	€37.5
	2040-2050					17x €1.5	€25.5
<b>Specific funding needs</b>	2020-2024					10x €0.5	€5
	2024-2030					15x €0.5	€7.5
	2030-2040					20x €0.5	€10
	2040-2050					20x €0.5	€10
<b>Total</b>		€0	€0	€0	€0	€125.5	€125.5

### A-12.b.4 Success factors

- European Community of Practice shares best practices; this is essential to effectively accelerate H4C development.
- Support to the H4C to act as a network that learns and transfers solutions across hubs and regions in the EU and beyond.

<sup>117</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

- Local/regional support from industries, other sectors, and local authorities. The local actors should be well-informed about the potential value of H4C and feel a need to pull.
- Other innovation programmes happening in the hubs.
- Long-term commitment, support, and investments from the EU, member states, regional authorities, civil society, financing institutions, and industry are key to facilitating the H4C emergence and development, the development of the innovative solutions, the installation of infrastructures, and of the logistics needed to enable the B2T deployment.

We suggest that:

- The EC supports hubs by providing funds for their establishment or development depending on their maturity and B2T plan (through P4Planet).
- All relevant regional stakeholders participate in defining and implementing the B2T plan and co-investing in and providing the required innovative solutions and infrastructures where possible.
- Through organisations that support regions (ECNR, ERRIN, VANGUARD), A.SPIRE can reach out to raise awareness, identify, and connect to the regions that can become H4C.

## A-13 Digitalisation

### Introduction

The innovation areas covering digitalisation are structured as follows:

1. **Digitalisation of the design phase of processes and materials.** Topics can be integrated in the early materials design and process phases through data and information sharing within and across value chains, with customers and within the R&D-ecosystem. Topics could include recyclability of end-of-life products. 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, 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 and with 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 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).
4. The demand for traceability of raw materials and products is increasing worldwide. Using sustainable, pest-free, traceable wood gives Europe's forest-based industries a competitive advantage. However, new, innovative technologies offer significant room for continued improvements. The concept of traceability also needs to include recycled raw materials. This requires multilateral, international co-operation and logistics that operate and maintain the traceability of source, collection, recovery, recycling, and transport of waste and materials.

The sections that follow outline the innovation areas P4Planet will focus on to drive the European Process Industries towards a new, digitised way of operating.

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

#### Text box 9: Development of digital technology

Digital technology development differs from other technology development in this roadmap. In most industrial innovation projects, an idea is matured and tested in practice at increasing scale to see whether it works. Multiple solutions are often developed in parallel and only one or two solutions are scaled up. The others either do not work or do not work efficiently enough. In digital innovation, fewer physical assets are used and projects can easily change the technology to make sure it is effective and functional. As a result, in the digitalisation programmes fewer projects are needed in the lower TRLs to account for failure. Digital technologies are more modular than most other technological innovations. As a result, multiple components are developed in lower TRLs and they are combined into a single application in TRL8.

Moving from TRL8 to TRL9 is different for digital technologies than for other technologies. In most cases, the implementation of digital technologies requires some investments in physical elements as well (e.g. sensors); however, the marginal costs for the digital solution are negligible if they exist at all. Once a digital technology is demonstrated in TRL8, commercial application can

be as simple as pressing a switch and going live with the technology in a commercial application. As a result, TRL9 demonstration is not programmed separately in the innovation programmes for digital technologies. Digital technologies can be combined with TRL9 demonstration of other technologies. Where relevant, this is indicated in the programmes but not included in the investments estimate.

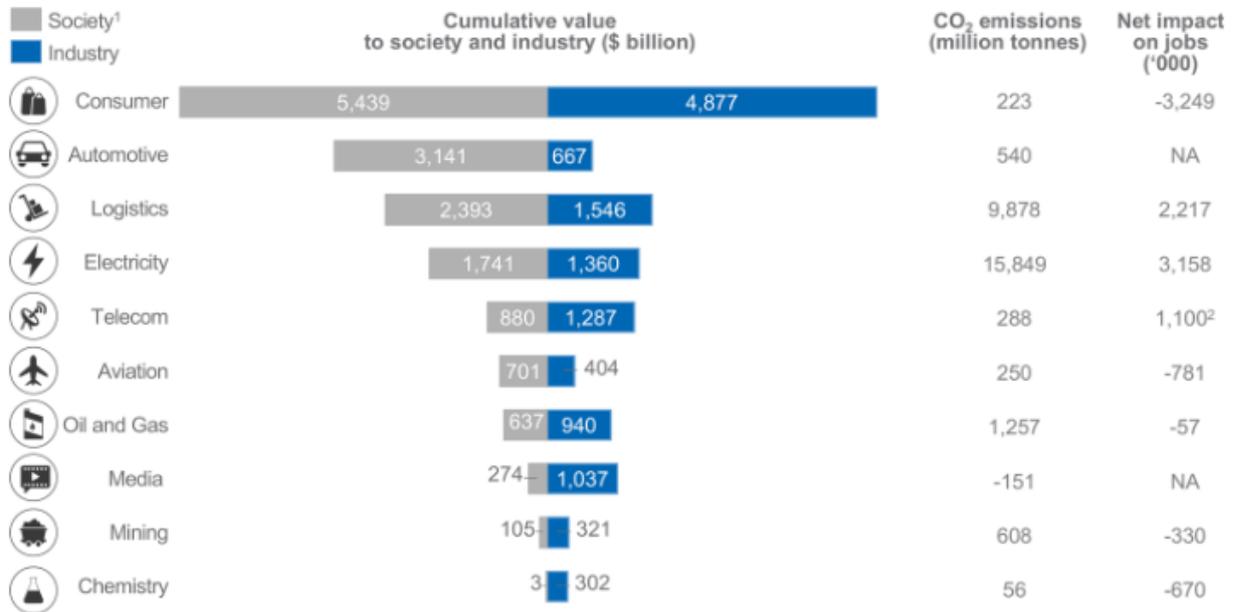
### **Impacts**

Digital technologies will enable emissions reductions through increases in yield and efficiency improvements in the process industry and across value chains. In many cases, digital technologies will be an essential part of other innovations in the process industry, e.g. through real-time information flows to support I-US, increasing the potential of power demand response and flexibility, and providing digital material passports or distributed ledger technologies that enhance the recyclability of materials. Since digital technologies are part of the solution, it is impossible to isolate the impact on GHG emissions or waste reduction.

Digital technologies can also increase the efficiency of current processes. Digitalisation's potential impact exceeds that of historic disruptive technological breakthroughs like the steam engine or automation (Larsson, 2019). The impact depends heavily on the process and the digital technologies that are applied. A study to the application of artificial intelligence to a cement kiln showed that an 11.6% efficiency gain could be achieved (McKinsey&Company, 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). Another study showed that the potential for increasing efficiency through digital processes varies from 5%-40% in the chemical industry, depending on the specific chemical industry and the step in the value chain (Deloitte, 2017), see Figure 12. These studies cannot be compared as scope and definitions of efficiency are different.

In 2015, the World Economic Forum launched the Digital Transformation of Industries (DTI) initiative, with a focus on quantifying the value at stake for both business and society. In one of its white papers, it assessed the impact of digital technologies on CO<sub>2</sub>-emissions and workforce (World Economic Forum & Accenture, 2016). The World Economic Forum's analysis shows that digitalisation can have a positive effect on the decoupling of economic growth and growth in CO<sub>2</sub> emissions and resource intensity. The estimated global impact is 26 billion tonnes of net avoided emissions between 2015 and 2016. Of the P4Planet industries, only the chemical industry was examined in more detail. The estimated net emission reduction in this period is 56 million tonnes of CO<sub>2</sub>, further specified to 60-100 million tonnes of CO<sub>2</sub> in a white paper dedicated to this sector (World Economic Forum & Accenture, 2017). This emission reduction can be achieved through digitalisation of processes through advanced automation and process control, predictive maintenance and real-time process, and quality and emission control. These elements are covered in innovation programme, Digitalisation of plant and plant operation.

**The ‘combined value’ to industry and wider society of digital initiatives across ten industries (cumulative, 2016-2025).**

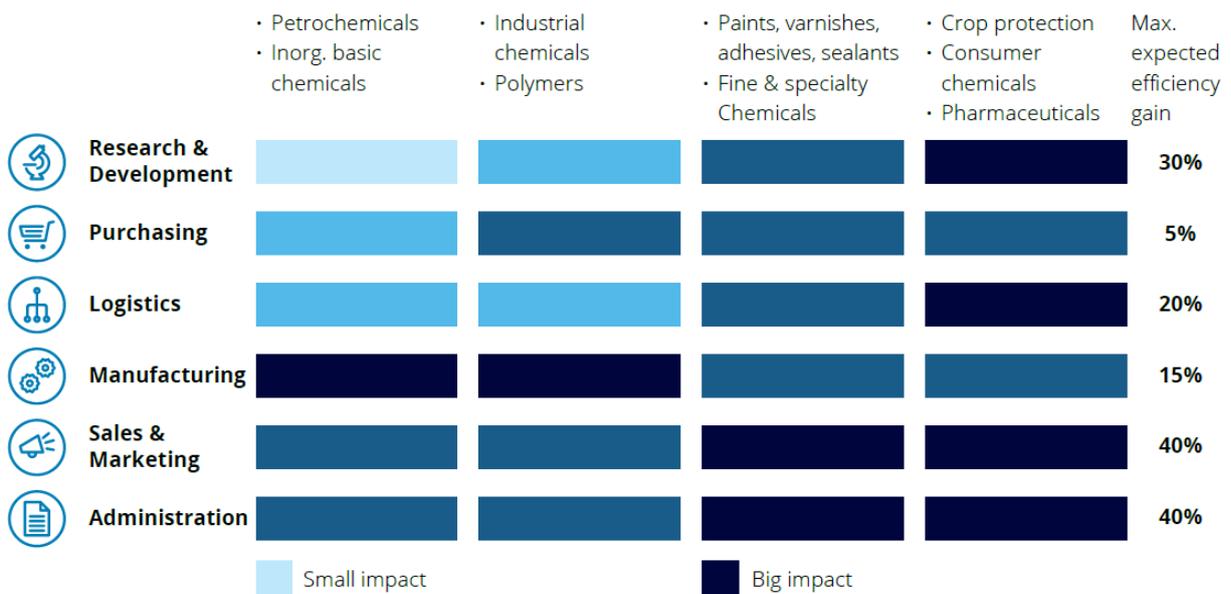


Note: <sup>1</sup> Total societal value at stake includes impact on the customers, society and environment. Impact on external industries has not been considered. <sup>2</sup>Excludes Extending Connectivity digital initiative.

Source: World Economic Forum / Accenture analysis

**Figure 11: Estimate of the global impact of digital initiatives on society (World Economic Forum, 2019)**

**Overview of implications of digitalization**



**Figure 12: Overview of implications of digitalisation in the chemical industry (Deloitte, 2017)**

## **Competitiveness**

The digitalisation innovation programmes boost competitiveness in several ways. Efficiencies will be increased across the process industries, resulting in substantial cost savings. Digitalisation enables a more rapid path to market of innovations, accelerating transformation and creating higher cumulative impacts until 2050 (GHG reductions, waste reduction, competitiveness). It also allows for the faster development and global roll out of European innovations. The business models that are only possible through innovations from these programmes (e.g. I-US business models) will increase competitiveness. Finally, the flexibility and optimisation unlocked by digital technologies allows for better optimisation of the energy system, decreasing infrastructure costs.

### **Success factors**

#### **Train the workforce in digital skills**

The digital transformation of the process industry will require greater competence in designing, performing, and implementing digital technologies. Moreover, Industry 5.0 is expected to merge the high speed accuracy of industrial automation with humans' cognitive and critical thinking skills. Data science and robotic experimental platforms will become enablers alongside conventional R&D, modelling, and the tools of process systems engineering. Digitalisation offers access to digital twins and AI-driven simulation environments. However, it is essential that conventional skills and knowledge of science and engineering are merged with the emerging capabilities of digital technologies to make the most of the digital revolution.

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 in 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 expertise. In some cases, this is considered a postgraduate expertise. There are emerging undergraduate courses and postgraduate training centres in digital technologies that underpin 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 materials science with respect to informatics, data science, machine learning, robotics, and AI.

To make best use of the digital transformation for the process industries sectors, it is increasingly important to enhance the digital skills of the existing industry workforce as well as the skills of new scientists and engineers. Digital skills requirements evolve rapidly, making it challenging to keep pace.

Engineers and scientists need to appreciate of the strengths and limitations of new digital technologies in areas such as data science, machine learning, robotics, and artificial intelligence, as well as the ability to apply systems thinking. This will need to be incorporated in university training to complement systems engineering and modelling skills that are already covered in modern programmes. Graduates of such programmes are not yet digital natives but are well-trained in applying the opportunities and limitations of the techniques. The bigger challenge is how 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 significant task that requires education on new tools and techniques and a change of mindset to place more trust in digital technologies while also retaining a critical view of limitations.

This success factor is addressed in innovation programme, Human resources, skills, and labour market (A-14.b).

## **Ensure cybersecurity**

The deployment of digital technologies will increase the vulnerability to cyberattacks, which pose significant risks to plant safety and plant operations and can result in plant downtime as well as harm to employees, customers, and other stakeholders. Working across value chains or within industrial-urban clusters with digital technologies will involve data sharing with other parties, even data considered confidential by the companies, accelerating the risks for data theft or misuse. Concerns about intellectual property protection, data ownership, and privacy must be addressed, and companies need to review internal procedures and policies frequently to effectively collaborate in digital ecosystems.

Discovering new and improved ways to manage this complex cybersecurity space is of the utmost importance for process industries to make the digital transformation successful. This development has to be undertaken 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 industrial cybersecurity initiatives. 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 servers and manufacturing hubs.

## **Organisations must prepare**

While digital transformation is already happening in the process industry, organising the innovations associated with digital technologies is a challenge for many. Time needed from staff to share expertise is a limiting factor in industries where margins are under pressure and there is little space for anything other than running the process.

The integration and interoperability of digital systems and platforms is a technical challenge and includes organisational alignment efforts, as information technology and operational technology responsibility is often spread across multiple departments.

At the board level, a digital strategy is needed that sets out the transformation needed and outlines the priorities and allocated time to experts.

## **Co-create with digital industries and other partners**

Crucial to the success of the digital transformation in the process industry is that the digital solutions are developed and suitable for application. Co-creation of these solutions with the digital industry is crucial, as is investing time to identify needs of network partners and understanding complexities.

## **The EC Digital Single Market Strategy**

Building a European data economy is key to the EC's digital single market strategy. The 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 new business models. Data sharing 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 enables connected value chains, industrial symbiosis, and technology transfer. Through open science, research communities are moving towards a more transparent environment for publishing research results, and smart access to such data will help industry innovation. Sharing data along value chains will enhance product qualities, reduce energy usage, and improve recycling/reuse efforts of water.

## **Digitalisation of process/product R&D**

Digital technologies will largely speed-up innovation if applied early in the product and process development stages, allowing more efficient idea-to-market processes, e.g. through more productive experiments by taking advantage of all previous results and company knowledge in the experimental design phase. Digitalisation will allow for the quick response to market and customer demands by integrating customers into the R&D processes. Digitalisation will integrate life cycle thinking and advance sustainability assessments towards the targeted solution.

R&D activities will be supported through advanced data analytics and AI. R&D will use complete sets of knowledge and available data available, receiving even lost or hidden knowledge. Digital technologies will manage the increasing complexity of future connected industries, which are expected to increase if circular economy will be implemented (e.g. recycling by design, new variable feedstocks, etc.).

Process and product research could be viewed differently depending on the process industry. In some industries, the first step is to develop a new product and then to develop 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 periods and the development of new products is limited by the existing production plants and their capabilities. Digitalisation will play an increasing role in the development of new products and in the development of new products 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 or digital twins for the complete chain of production process. These models can be used 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.

Many positive effects can be reached through product digitalisation, the process development process, and the suitable handling of all information and data produced during this process. These data could be used to design production processes in a 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 that will accompany the product through its whole life cycle, e.g. more efficient recycling processes.

After the processes begin operation, the online data produced during operation (process variables in combination with product quality features) could help develop better products with the final aim to realise a fully auto-adaptive process in the future.

## A-13.a Digital materials design

This programme focuses on the development of new digital technologies that support all development phases of innovative materials. The digital capabilities will drastically increase the efficiency in the development of tailored materials. This provides value to the end-users and enables materials to be produced sustainably from bio-based or recycled feed material and be recycled or re-introduced in the production cycles of a circular economy. Data-sharing with customers and the early integration of product end-of-use handling in the R&D-processes will ensure a quick response to market and customer demands. Topics such as safe-by-design, life cycle assessment, circularity-by-design, and feedstock complexity must be tackled in the R&D design and experimentation stage and in connection with the production processes. Digital tools and databases across complex R&D pipelines must be developed. Access to and exchange of data beyond a company's borders will increase in importance, making data and IP protection a challenge.

With the goal of making R&D more efficient and effective, materials modelling and simulation has become essential to 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. Models are too complex and computationally intensive for the simulation of final products, so they must be embedded in a multi-scale approach to predict the end use properties of a product. Machine learning and artificial intelligence technologies should be considered 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. Tightly integrating process design and model-based materials design is envisioned as a design paradigm change. The safety and sustainability of the production processes and recycling or reuse can be factors in the materials design phase so that an early life cycle assessment is possible.

### A-13.a.1 Innovation objectives

- **Reduced costs and improved efficiency of the R&D process** by applying digital R&D within early product/process design and development stages, which hasten 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 model-supported material design process. A model-based approach will integrate a 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 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, start-ups, academia, and the process industry.
- **Improved reproducibility of results** by applying digital R&D to analyse large volumes of data, increase the scale-up speed due to the capacity to experiment faster and in an accurate manner, while 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, accounting for a 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, tools, experience, and best practices provide effective communication among involved innovators/stakeholders, resulting in increasing the effectiveness and commercial benefits of their activities.
- Develop standards for traceability in recycling processes, transport and end-of-life waste that can be accepted at regional level as well as in international co-operation. Investigate how to use and adapt tracking technologies such as RFID, DNA marking and blockchain technologies to secure the chain-of-custody.

### A-13.a.2 Programming

1. Materials design
  - a. 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 life cycle assessment and end-of-use product and materials handling.
    - a. Integrate computational tools (including data-based models, artificial intelligence) into materials design will be done before 2024 in four projects of €3 million (TRL4-6).
    - b. Implement digital supported life cycle assessment methodologies and software including the early product development phases will be done between 2024 and 2030 in four projects of €6 million (TRL4-6).
  - b. Improve the efficiency of the materials design process and the computational tools used 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, new 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. Integrate technologies previously developed for implementation of digital twins of products from the beginning of design phases will be done between 2024 and 2030 in four projects of €6 million (TRL7-8).
  - c. Develop 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 information by the development of suitable representations and search algorithms, including literature, patents, and open and proprietary data.
    - d. Platforms for data sharing along innovation ecosystems to foster knowledge- and data-driven collaborative R&D will be done between 2024 and 2030 in three projects of €5 million (TRL4-6).
  - 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.
    - e. New data platforms for knowledge sharing and best practices among R&D actors will be done before 2024 in three projects of €2 million (TRL4-6).
    - f. Software tools aiming at supporting fully model-base adaptive R&D process will be done between 2024 and 2030 in four projects of €6 million (TRL7-8).
2. Integration of materials and formulations design with process design
  - b. Include information early on about the production process and the feedstock into the materials design process to arrive at the most sustainable, efficient, and safe production processes.

- a. Digital technologies for full product eco-design by managing complex interactions between different supply chains will be done between 2024 and 2030 in four projects of €6 million (TRL7-8).
- c. Develop more fundamental characterisations of the (secondary) resources as input for more flexible production processes so that the overall sustainability can be optimised.
  - a. Characterisations of alternative feedstocks as input for more flexible production processes will be done before 2024 in three projects of €2 million (TRL4-6).

This programme only brings the technology to TRL8. Afterwards, it can be used in integrated TRL9 demonstrations of other innovation programmes where the produced materials or wastes coming from materials play an important role. This is the case in innovation programmes, Inherent recyclability of materials (A-10.b), Demonstration of industrial-urban symbiosis (A-11.a), CO<sub>2</sub> and CO mineralisation to produce building materials (A-7.b), and Catalytic conversion of CO<sub>2</sub> to chemicals/fuels (A-8.b).

This innovation programme is directly linked to the innovation programme, Digital process development and engineering (A-13.b), because the results can be used for process design to produce the digitally designed materials.

### A-13.a.3 Investment needs

Table 34: Investment needs in € million<sup>118</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Materials design	2020-2024		4x €3 + 3x €2				€18
	2024-2030		4x €6 + 3x €5	4x €6 + 4x €6			€87
Integration of materials and formulations design with process design	2020-2024		3x €2				€6
	2024-2030			4x €6			€24
<b>Total</b>		<b>€0</b>	<b>€63</b>	<b>€72</b>	<b>€0</b>	<b>€0</b>	<b>€135</b>

<sup>118</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-13.b Digital process development and engineering

Process design is increasingly done using reliable predictive simulation models of processes, pieces of equipment, and plants. However, several items still prevent the use of the full potential of the model-based approach. Fundamental data, e.g. of thermodynamic properties or kinetics, is often missing and expensive to generate experimentally. Building fundamental models is demanding and absorbs the capacity of high level experts over long periods of time, so that many process elements may not be described by rigorous models. In many cases, model simulations are still computationally 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 GHG emissions-free electricity, are usually not available. Models for the design phase are rarely used in the production phase of the process life cycle, and information on the behaviour of the real plant and its modifications is rarely fed back to the design model. Consequently, the experience is not available from the operation of the designed plants and processes, that is, when similar plants are designed, or modifications are planned. Paving the path to digital twins 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 feedstock changes due to recycling resources 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.

### A-13.b.1 Innovation objectives

Specific targeted benefits are:

- Digital twins 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.

### A-13.b.2 Programming

The objective is to 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 resources in a circular economy.
2. Platform design and implementation 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. Using operational data to update models 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.

This is achieved through three sets of projects:

- Digital twins of large-scale production processes, including heterogenous (physics and data-based) models of different granularities, will be done before 2024 in four projects of €5 million (TRL4-6).
- Sector specific vendor-neutral model platforms will be developed between 2024 and 2030 in four projects of €5 million (TRL4-6).
- Implementation and demonstration of vendor-neutral models will be done between 2024 and 2030 in four projects of €10 million (TRL7-8).

The tools developed in this innovation programme should be applied to all P4Planet processes created towards 2050. Integrated digital engineering will ensure maximum resource and energy efficiency, along the whole life cycle of a plant, covering product and process development, plant engineering, procurement, plant construction, commissioning, later operation, as well as plant flexibility, extensions, and reuse for next generation and new products.

The technology can be demonstrated in TRL9 projects of all innovation programmes where new processes are developed, or where existing processes are improved. This can be in Integration of renewable heat and electricity (A-1.a), Advanced heat reuse (A-2.a), Using hydrogen in industrial processes (A-5.b) and CO<sub>2</sub> utilisation in concrete production (A-7.a).

This innovation programme is directly linked to the innovation programme Digital materials design (A-13.a), because the results of that innovation programme can be used for the design of processes that have to produce the materials.

### A-13.b.3 Investment needs

Table 35: Investment needs in € million<sup>119</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Digital process development & engineering	2020-2024		4x €5				€20
	2024-2030		4x €5	4x €10			€60
<b>Total</b>		€0	€40	€40	€0	€0	€80

<sup>119</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## Digitalisation of Plants

Industrial processes and related process chains are 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 produce customised materials.

New digital-enabled solutions are necessary to improve process control and operations reliability. These solutions will optimise the processes themselves and will 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 must be robust, flexible, and transparent to all users. These applications should be usable 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-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 indicates the delivery of resources with key information such as timing, quality, and quantity, and means that the plant can adjust its production schedule and recipe in real-time for additional throughput and efficiency of a quality product. This improved product, along with the information, can be delivered downstream for additional efficiency gains in every step of the value chain. Efficiency gains come from on-stream-time, resource 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 in a reduction of 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 suitably digitised way, a full digital model of a plant or process/plant operation will be necessary to develop. The kind of plants and plant operations also varies 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 still based on operator experience in some cases, because the existing models can only describe a part of the process or is too incorrect to allow a closed loop control. In such cases, decision support systems based on data or symbolic knowledge can help the operator run the plant. The newest model predictive control techniques based on complex, sometimes hybrid-models are becoming state of the art, e.g. in chemical production plants. The target is full control of single processes with the aims of improved product quality, optimal energy, and resource efficiency and minimal production costs. The coordination of the control of interconnected processes is important. Other areas that can be improved by digitalisation solutions include production scheduling and maintenance operations. One disadvantage is that both items are highly interconnected but operated independently because they are very often driven by different departments that are often uncoordinated. A possible solution 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 that way. Better inter-process scheduling plays an important role to reach higher resource and energy efficiencies. Optimal maintenance strategies combined with

improved scheduling increases the production yield (with the effect of better energy and resource efficiency) and reduces production costs. The goal 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 this information process control, production scheduling, material allocation, and maintenance actions are not possible. Powerful, 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.

Data lineage (data provenance) will play a crucial role to manifesting valid and reliable information, 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 evaluate the reliability of its input data.

The availability of alternative energy from renewable sources is linked to plant operation. Solutions for the flexible and adaptive use of different kinds of energy and their coordination between different plants, sites, or industries are necessary. Suitable optimisation strategies could help find an optimal solution in this environment with more contradictory demands.

The movement towards a circular economy and the utilisation of electric power from renewables will place higher demands on plant and process flexibility in terms variations of load, feedstock, and product specifications.

For these tasks new, more powerful, and fully integrated solutions are necessary that can only be reached by powerful digitalisation technologies. The objective must be to reach a highly flexible, easy to handle, and generalised solution for the optimisation of processes and for the complete process chain of a company, even between companies and industries. Digital twins for plants, processes, and products that 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. In 2050, a process enterprise will have access to accurate, curated, and readily accessible operational data to support both routine (automated, autonomous) workflows and analytics-supported optimisation.

### A-13.c Digital plant operation

The process industry includes a variety of processes. 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 generally too incorrect to allow a closed loop control. In such cases, decision support systems (e.g. based on machine learning/artificial intelligence technologies) can help the operator to run the plant. Advanced operator interfaces are an important precondition. The newest model of predictive control techniques based on complex, sometimes hybrid models are state of the art in parts of the process industry but have yet to be fully exploited. Machine learning control is another new trend and enlarges the available tools for online process control. The target is the complete dynamic control of single processes with the objective of improved product quality, optimal energy, and resource efficiency, considering all environmental issues at minimal production costs. The coordination and optimisation of the control of interconnected processes is also important. Regarding production scheduling, a direct connection to Autonomous integrated supply chain management (A-13.e) is given here. One of the most important areas is flexibility: in using different kinds of energy or resources with different properties, in reaching a lot size of 1 if needed, or in using a different process route inside the company in case one plant runs currently a maintenance action.

Depending on the process, different combinations of low level control, direct product quality control, and overall supervisory control solutions are necessary to reach final targets. In the overall supervisory control, all environmental aspects must be integrated, like CO<sub>2</sub> emissions, other pollutions, and energy and water consumption. New and disruptive techniques are necessary. One solution could be a level of control over a suitable combination of first principal models based on physical/chemical relationships and data-driven models constructed by machine learning/artificial intelligence approaches and semantic models. Based on these models, the scope of model-based control and model-based optimisation will be enlarged to all possible areas. The interaction between operators and engineers with such solutions should be considered and new techniques for operator interfaces must be developed.

Product quality, production yield, and costs have long been the targets of process control. Energy and resource efficiency and the reduction of any kinds of pollutions did not play a central role in all industries. The integration of all resource efficiency and environmental aspects have to be considered:

- *Energy:* 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, Flexibility and demand response [see A-1.d]). The use of digital capabilities will provide stable industrial operations and grid stability in an increasing renewable energy landscape. E.g. the intelligent prediction of energy consumption and energy availability by use of artificial intelligence technologies like machine learning solutions will play a significant role. Suitable optimisation strategies could help to find a solution in this complex environment, in many cases with contradictory demands. The final and most important objective is to dramatically reduce the energy usage of fossil fuels.
- *Water:* In many process industry plants, water plays an important role as raw material/feedstock or as process water, e.g. for cooling purposes. Clean drinking water will become one of the most challenging resources 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. Water purification should also be considered. Flexible algorithms should be developed and implemented to support water operation decision-making, risk management, and water use considerations on integrated system level and based on suitable models.

- *Pollutions*: The emission of CO<sub>2</sub> is directly connected to energy consumption of plants, and should be reduced drastically in the next few years. Additionally, new production processes will be developed based on hydrogen instead of carbon usage for the process itself or as energy source, and these processes should be controlled. The integration of pollution aspects into process control of single plants and the optimal coordination of several plants of one company by interconnected control solutions will help to reduce CO<sub>2</sub> emissions. Beside CO<sub>2</sub>, all other possible pollutions that negatively effect the environment should be considered on the different levels of process control. This is highly depending on the nature of the plant.
- *Waste*: The avoidance of any kind of waste production should become an essential part of process control solutions. Suitable KPIs should be developed and directly integrated in the supervisory control of single plants. In cases where waste cannot be avoided because of process constraints, information about the waste, its ingredients, and its amount should be transferred to company's or industry's parkwide waste stream management systems.

Cybersecurity is directly connected to the digitalisation of the process industry. 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 security of IT solutions, but it will address risks in the field of process safety based on cyber attacks to process control solutions coming from outside. The above-mentioned developments should take this risk into account and solutions need be found to detect attacks to process control systems as early as possible. Solutions could 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 that are caused by a cyber attack.

Digital twins play an important role in all the above aspects, as well for processes as also for products. Digital twin technology should be further developed to fulfil all demands of process control purposes (innovation programme, Digital plant operation in A-13.c). Digital twins are not 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). Active and agile elements (e.g. based on software agents) must be implemented that can communicate to become the digital twin, which is a very powerful tool to solve complex and distributed optimisation problems. To help digital twins orient themselves in real world environments, semantic models of the complete production flow and many of its aspects are essential. An ecosystem of agile digital twins suitable for all the above-mentioned tasks should be developed. This way, digital twins can achieve a self-driven and self-organising production.

Modern process technologies have become more complex, requiring highly qualified personnel to handle complex information streams. It is also important that predictive maintenance increases to reduce unscheduled downtimes, identify (critical) process states, and assess of wear and tear of equipment. Intuitive human machine interfaces that efficiently support people at the workplace become increasingly important. Technologies like smart glasses, augmented reality, and data analytics combined with smart hand-held devices provide previously unknown possibilities for information, visualisation, and interaction. The potential of the combinations of these technologies still must be explored. The conventional control room will transform to provide smart information, visualisation, and offsite interaction for the operator or the maintenance crew onsite. By providing the pre-processed information tailored to the current situation, decision-making in complex situations and work safety will be enhanced. This will be complemented by knowledge management technologies to represent either written (documented) information or the knowledge of experienced operators.

In the environment of Machine-to-Machine and Human-to-Machine, the humans-in-the-loop concept is 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. It provides support that combines situational 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, dramatically improving safety and effectiveness in operations at the same time.

#### **SPIRE projects this programme builds on**

**INEVITABLE** develops a digitalised monitoring technology for an optimised and improved performance of manufacturing processes. It will come to TRL7 in 2022 with 3–3.5 kgCO<sub>2</sub>/t final product reduction and non-ferrous rejection waste will reduce from 12% to 8%-9%. It will become competitive from the high steel quality it will deliver.

**COCOP** integrates unit-level sub-problems in plant operations into a plant-wide optimal schedule at TRL6 with potential to TRL9 in 2025 with CO<sub>2</sub> reduction potential of 8%. It has a strong environmental impact due to the reduced copper content in the slags and it leads to an increase PSC brick lining lifetime that reduces waste bricks.

**MONSOON** developed a model-based control framework to optimise process efficiencies up to TRL7 with the potential to move forward to TRL9 in 2025. This framework leads to significant GHG emission reduction and waste reductions (e.g. plastic waste reduction of 12%-15%). It can be clustered with COPRO and FUDIPO.

#### **A-13.c.1 Innovation objectives**

- 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 is not possible.
- Early detection of possible cyber attacks to process control systems and beginning 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.

#### **A-13.c.2 Programming**

The following activities are programmed:

- Establish an ecosystem of digital twins suitable for process control purposes (2021-2023), two projects, €8 million each (TRL1-3).
- Decision support systems and suitable operator interfaces for class of processes that cannot be operated fully automatically (2021-2025), three projects, €5 million each (TRL4-6).

- Fully dynamic cognitive control of single processes integrating all aspects (quality, costs, environment), (2022-2026), four projects (two before 2024 and two after 2024), €6 million each (TRL4-6).
- Integration of anti-cyber attack solutions into process control system (2023-2025), two projects, €5 million each (TRL4-6).
- Machine learning/artificial intelligence techniques suitable for cognitive process control (2021-2024), four projects, €5 million each (TRL4-6).
- Techniques for the detection of cyber attacks on process control systems and suitable counteractions (2021-2023), three projects, €4 million each (TRL4-6).
- Demonstration of cognitive control of typical classes of processes (2026-2028), three projects, €6 million each (TRL7-8).
- Demonstration of cognitive supervisory control of interconnected plants, (2027-2030), four projects, €8 million each (TRL7-8).

The technology developed in this innovation programme can be demonstrated at TRL9 in every innovation programme where existing or new plants/processes are operated. For example, this can be in the innovation programmes, Breakthrough efficiency improvement (A-9.b), Using hydrogen in industrial processes (A-5.b), Electricity-based heating technologies (A-3.b), Catalytic conversion of CO<sub>2</sub> to chemicals/fuels (A-8.b), Flexibility and demand response (A-1.d), Integration of renewable heat and electricity (A-1.a), Advanced heat reuse (A-2.a), and Wastewater valorisation (0).

### A-13.c.3 Investment needs

Table 36: Investment needs in € million<sup>120</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Digital plant operation	2020-2024	2x €8	3x €5 + 2x €6 + 2x €5 + 4x €5 + 3x €4				€85
	2024-2030		2x €6	3x €6 + 4x €8			€62
<b>Total</b>		<b>€16</b>	<b>€81</b>	<b>€50</b>	<b>€0</b>	<b>€0</b>	<b>€147</b>

<sup>120</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

### A-13.d Intelligent material and equipment monitoring

For handling 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. Powerful and intelligent online sensors or sensor networks are necessary and solutions should be available to handle the huge amounts of online data from these sensors and to extract useful knowledge. These data should be connected with relevant, sometimes unstructured information.

The focus of the sensor developments should be on properties of raw materials and on intermediate and final products. Sensors should be developed that can fully describe the environmental aspects of plants and processes like energy usage and any kind of pollution and can provide predictive maintenance in real-time. Wherever possible 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 that uses the same backbone for ease of implementation.

Another objective is to solve the industrial Big Data problem as a basis to developing 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 yet only a small percentage is being used. The transformation of data into smart, useful information will require the development of hard and soft solutions based on new computing techniques. Highly important are 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 artificial intelligence 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 to avoid unplanned stoppages due to machinery failures. To reach the optimal effect of new maintenance strategies, coordination between maintenance and production scheduling (refer to A-13.e) is essential. A large disadvantage in this area is that both items are highly interconnected yet operate independently. They are driven by different departments and thus are uncoordinated. A possible solution could be a system of digital twins of products and processes that is able to solve online optimisation problems and offer the possibility of self-organised production systems.

The above-mentioned plant monitoring regarding equipment failure should be expanded by other monitoring tasks regarding environmental targets like energy, raw materials, and process water consumption, CO<sub>2</sub> emissions, other pollutants, and any kinds of waste. These monitoring results are the inputs for the supervisory control solutions of single plants and process chains described in A-13.e and the basis for a factory and site-level wide monitoring of the whole production efficiency and many environmental aspects. Parameters of a product life cycle assessment have to be integrated in the plant monitoring strategy.

### **SPIRE project this programme builds on**

**COPRO** demonstrated at TRL6-8 in petrochemical sites, consumer products, food canning, viscose fibres the improvement of energy and resource efficiency led to a GHG emissions reduction by 10%. A reduction of 2%-10% GHG emissions and a significant competitive impact are anticipated. An SME needs to roll out the system.

**RECOBA** developed an in-line melt measurement and a new temperature sensor technology and can, by extending the functionality, bring the system to TRL7. RECOBA is transforming the design and implementation of batch processes that will reduce GHG by 600,000 tonne/year. Already at TRL5, development to TRL7 will require improved sensor functionality with the expectation of reaching TRL 9 by 2030 with development of dynamic process models.

#### **A-13.d.1 Innovation objectives**

- Powerful and intelligent online sensors or sensor networks (wireless where possible) with a focus on properties of raw materials and 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 (including checking and improving quality of the data) and methods to extract automatically and in real-time acquire useful information.
- Solutions to detect possible equipment failures early automatically by intelligent condition monitoring system, e.g. empowered by machine learning/artificial intelligence 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, “Digitalisation of industrial-urban symbiosis” in A-13.f).
- Expand plant/process monitoring systems to always reveal the full environmental footprint of the running process in real-time and initiate counteractions if there are deviations from optimal conditions.
- Integration of life cycle assessment into the plant and site-wide monitoring strategies.

#### **A-13.d.2 Programming**

- Early detection of equipment failures and techniques for predictive/prescriptive maintenance actions (2022-2025), four projects, €5 million each (TRL4-6).
- Fully automatic pre-processing of all data (2021-2023), two projects, €8 million each (TRL4-6).
- Expanding process monitoring system by all relevant environmental and life cycle assessment aspects and initiation of counteractions (2021-2025), two projects, €6 million each (TRL4-6).
- Automatic real-time extraction of knowledge from huge amounts of process data (2021-2024), three projects, €5 million each (TRL4-6).
- Intelligent sensors and sensor networks for products, processes, plants, and environmental aspects (2021-2024), three projects, €6 million each (TRL4-6).
- Coordinate maintenance actions with production scheduling (2025-2028), two projects, €6 million each (TRL7-8).
- Integrate cognitive and site-wide maintenance solutions (2026-2030), three projects, €6 million each (TRL4-6).

The technologies can be applied everywhere complex plants are managed, e.g. in Electricity-based heating technologies (A-3.b), Electrochemical conversion (A-4.a), Electrically driven separation (A-4.b), Flexible CO<sub>2</sub> capture and purification technologies (A-6.a), CO<sub>2</sub> utilisation in concrete production (A-7.a), CO<sub>2</sub> and CO mineralisation to produce building materials (A-7.b),

Catalytic conversion of CO<sub>2</sub> to chemicals/fuels (A-8.b), Utilisation of CO<sub>2</sub> and CO as a building block in polymers (A-8.c), and Utilisation of CO to chemicals/fuels (A-8.d).

### A-13.d.3 Investment needs

Table 37: Investment needs in € million<sup>121</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Intelligent material and equipment monitoring	2020-2024		4x €5 + 2x €8 + 2x €6 + 3x €5 + 3x €6				€81
	2024-2030			2x €6 + 3x €6			€30
<b>Total</b>		€0	€81	€30	€0	€0	€111

<sup>121</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## Digitalisation of connected processes and supply chains

This innovation area focuses on digitalisation 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 with downstream actors. It includes integrated waste management (wastewater 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). There is an overlap with the innovation programme, Digital plant operation (see A-13.c). 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 planning to optimise on company level and on the full upstream supply chain level to achieve efficiency improvements that reduce the carbon footprint. Similar integration can be achieved with energy procurement (electricity, heat, others), to enable demand side management.

Industrial symbiosis (see the innovation programme, Demonstration of industrial-urban symbiosis in A-11.a) can be digitally coordinated to couple production units/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 with downstream actors. It also includes integrated waste management optimisation (wastewater treatment, thermal treatment, other by-products). When covering the full supply chain, it enables the transfer of information across the supply chain in real time. This enables agile, demand-driven supply chains, customised products optimised for sustainability, and the facilitation of reuse and recycling by digital fingerprints/digital twins of products along the supply chain. This includes the reverse optimisation of the process chain of the material production, e.g. by 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 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.

### A-13.e Autonomous integrated supply chain management

This innovation programme aims to find solutions for integrated planning, scheduling, and control within plants and supply chains. It will cover the first two levels described above.

Supply chains can be complex, with recycle loops within the plants and sites and within the assembly of the final products and their recycling. Materials may reside within this chain for months. Along all 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 and creates 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, some flexibility opens up, as the consumption of electric power must be adapted to the availability of GHG emission-free power to reduce the CO<sub>2</sub> footprint and the cost of energy. This same principle also applies to thermal energy flexibility.

These factors lead to increased pressure to dynamically manage processing and supply chains to simultaneously realise energy and resource efficiency, an agile response to changing customer demands, and prices for resources and energy and availability of green power . Digitalisation is key to achieving this target.

#### A-13.e.1 Innovation objectives

1. Solutions for integrated planning, scheduling, and control within plants:
  - a. Improved digitally enabled planning and scheduling to optimise efficiency and reliability of supply in the presence of uncertainties on resources, prices, and resources.
  - 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. Integrate predictive maintenance with planning and production scheduling.
  - e. Integrate 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 life cycle assessment monitoring and optimisation
3. Data integration along the supply chain and across sectors:
  - a. Include 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. Facilitate the reuse and recycling of products by digital fingerprints along the supply chain, based on standardised product descriptions.
  - c. Enable an increase of the use of secondary resources through the real-time characterisation of waste streams.

### A-13.e.2 Programming

- Integrated planning and scheduling of plants and sites, four projects, €6 million each (TRL4-6), 2021-2028.
- Real-time REI and life cycle assessment from cradle to gate, three projects, €5 million each (TRL4-6), 2021-2024.
- Concepts for data sharing along the supply chain in the process industries, four projects, €3 million each (TRL4-6) , 2021-2023.
- Concepts and standards for digital fingerprints of materials and products, three projects, €2 million each (TRL4-6) (see also Upgrading secondary resources in A-10.c) , 2021-2023.
- Integration of planning and scheduling along the supply chain, four projects, €6 million each (TRL4-6), 2024-2027.
- Platforms for data sharing along the supply chain, 2024-2027, three projects, €6 million each (TRL4-6).
- Information transfer along the supply chain, three projects, €5 million each (TRL4-6), 2024-2027.
- Integrated planning and scheduling of plants and sites, three projects, €10 million each (TRL7-8), 2025 – 2030.
- Real-time resource efficiency and life cycle assessment monitoring from cradle to gate, two demonstrations, €8 million each (TRL7-8), 2025-2027.
- Integration of planning and scheduling along the supply chain, two projects, €8 million each (TRL7-8), 2028-2030.
- Demonstration of digitally integrated supply chains with minimised carbon footprint, three projects, €10 million each (TRL7-8), 2028-2030.

When demonstrated, the technologies can be applied in innovation programmes, Breakthrough efficiency improvement (A-9.b), Innovative materials of the process industries (A-10.a), Inherent recyclability of materials (A-10.b), and Upgrading secondary resources (A-10.c).

### A-13.e.3 Investment needs

Table 38: Investment needs in € million<sup>122</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Autonomous integrated supply chain management	2020-2024		4x €6 + 3x €5 + 4x €3 + 3x €2				€57
	2024-2030		4x €6 + 3x €6 + 3x €5	2x €8 + 2x €8 + 3x €10			€119
<b>Total</b>		€0	€114	€62	€0	€0	€176

<sup>122</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

### A-13.f Digitalisation of industrial-urban symbiosis

This innovation programme focuses on the development of digital technologies. These technologies enable urban-industrial symbiosis so material cycles can be closed within the industrial sector and 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 to maximise the overall energy and resource efficiency, to minimise the environmental impact, and provide all partners 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 confidential technical and economic constraints are tightly connected, so an overarching coordination and distribution of benefits is becoming necessary. When progressing to urban-industrial symbiosis, uncontrollable and partly unforeseeable consumer behaviours and the presence of complex connecting infrastructures (e.g. the collection and sorting of waste streams) makes 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.

The digitalisation of industrial symbiosis currently is at TRL2-5. Within the P4Planet programme, solutions for the systematic investigation of options for industrial symbiosis have already been developed. These must be rolled out to real applications in H4C within the next few years. Solutions for the real-time management and optimisation of connected production sites beyond the borders of individual companies have reached only TRL2-3. The legal side of such collaborations needs to be explored. The demonstration of the first prototypes of integrated management solutions should be achieved in 2025, roll out of digital solutions in H4C should be in 2030. Integrated water management between industrial sites and reusing wastewater streams where possible to reduce the intake of drinking or purified water is a field that also promises reductions of the consumption of energy and resources and must be supported by digital technologies.

Urban-industrial symbiosis is 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 improvements to heat network efficiency. Integrated wastewater management can also easily extend to I-US. The reuse of urban waste by the process industry is not very developed. Recycling complex materials from urban waste such as plastics depends on the separation of the waste streams into fractions that can be treated and reused efficiently. Tracking materials and digital passports of end-products is of crucial importance. The separation of waste streams must be digitalised. 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 TRL4 or higher (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, developments to the digital support technologies for urban-industrial symbiosis will address the challenges that arise when it is broadened and deepened.

#### A-13.f.1 Innovation objectives

1. Integrated, real-time systems management for urban-industrial symbiosis:
  - a. Digitalisation of integrated industrial and urban-industrial water and wastewater treatment and distribution systems and of the utilisation of waste heat by industry

- and municipalities. The focus will be on the connection of separate management and control systems and the introduction of an overarching, real-time management plan 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 resource 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. Legal, economic, and organisational aspects must be considered.
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-ferrous 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 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 product life cycle, if needed it can be secured using 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.

### **A-13.f.2 Programming**

- Concepts for full digitalisation of plastic recycling value chains, four projects, €3 million each (TRL4-6), 2021-2024.
- Tracking of material compositions, concepts, and data formats, three projects, €3 million each (TRL4-6), (could potentially be CSA), 2021-2023.
- Real-time management of wastewater and waste heat networks, four projects, €6 million each (TRL4-6), 2021-2025.
- Real-time management and optimisation of industrial symbiosis, first call to reach TRL5 by 2024, four projects, €4 million each (TRL4-6).
- Advanced sensing and automation for recycling of materials, 2021-2025, 6 projects, €5 million each (TRL4-6)
- Information platforms on waste streams in Europe, three projects, €6 million each (TRL4-6), 2021-2024.
- Real-world application of systems for the support of industrial symbiosis in hubs for circularity, €18 million (TRL7-8), 2021-2025.
- Advanced sensing for industrial symbiosis, €24 million (TRL7-8), 2021-2025.
- Advanced sensing and automation for recycling of materials, four projects of €8 million each (TRL7-8).
- Information platforms on waste streams in Europe, two projects, €10 million each (TRL7-8).
- Legal and business aspects of industrial symbiosis, CSA €1.5 million, 2021-2023.
- Business concepts for information platforms for waste streams in Europe, CSA €1.5 million, 2022-2023.
- Real-time management and optimisation of industrial symbiosis, to reach TRL6/7 by 2028, three projects, €6 million each (TRL4-6)

- Full digitalisation of materials recycling value chains, four projects, €6 million each (TRL4-6), 2025-2028.
- Prototypes for material tracing along the value chain, four projects, €5 million each (TRL4-6), 2024-2027.
- Real-time management and optimisation of industrial symbiosis, 2025-2028, three projects €6 million each (TRL7-8).
- Platforms for material tracing, 2028-2030, three projects, €10 million each (TRL7-8).
- Standardised formats for materials tracking, one CSA, €4 million, 2024-2027.

When demonstrated, the technologies can be applied in innovation programmes Demonstration of industrial-urban symbiosis (A-11.a), Wastewater valorisation (0), and Upgrading secondary resources (A-10.c).

### A-13.f.3 Investment needs

Table 39: Investment needs in € million<sup>123</sup>

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Digitalisation of industrial-urban symbiosis	2020-2024		4x €3 + 3x €3 + 4x €6 + 4x €4 + 6x €5 + 3x €6	€18 + €24 + 4x €8 + 2x €10		€1.5 + €1.5	€206
	2024-2030		3x €6 + 4x €6 + 4x €5	3x €6 + 3x €10		€4	€114
<b>Total</b>		<b>€0</b>	<b>€171</b>	<b>€142</b>	<b>€0</b>	<b>€7</b>	<b>€320</b>

<sup>123</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

## A-14 Non-technological aspects

As described in Section 4.15, people and non-technological aspects are key to technological change and implementation. They first define the problem and then improve (a) the effectiveness, implementation, and sustainability of technological innovations, and (b) the competitiveness of the process industries. Based on this, non-technological aspects are addressed as follows:

1. **Integration of non-technological aspects in calls:** Non-technological actions that are specific for innovation programmes and key to the success of innovation will be integrated as non-technological features in the process of developing calls for proposals. This process is described in the following section.
2. **Standalone, non-technological actions** of a more generic nature completing the technological perspective: these will be tackled across the board, identifying recent and future non-technological needs. For this category, all four topics from the conceptual framework are covered (see 4.15). Some topics are covered in the innovation programmes described in A-12, and human resources, skills, and labour markets are covered in a separate innovation programme in this appendix.

Activities must be compatible with existing initiatives and evidence for the sector.

### **SPIRE projects this innovation area builds on**

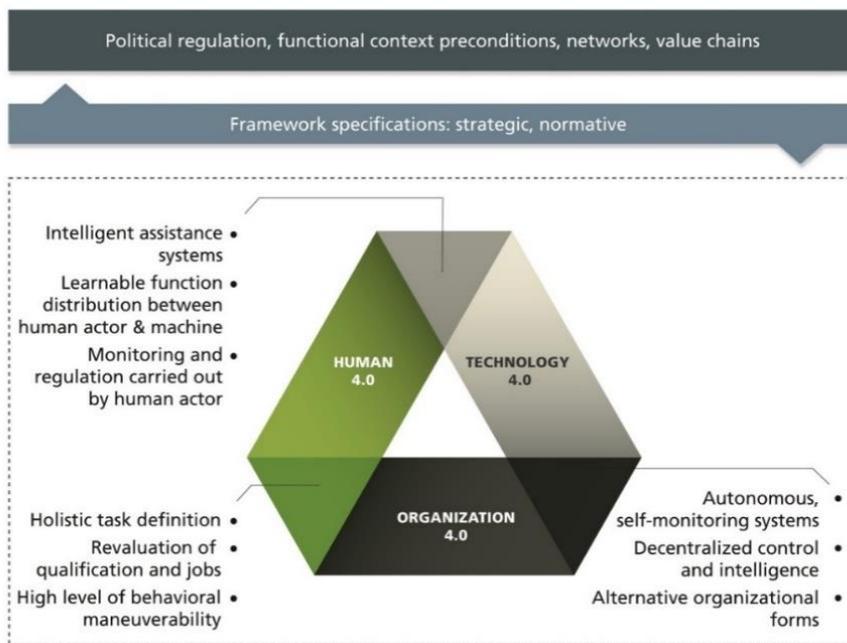
**MEASURE** will provide a roadmap highlighting a life cycle based evaluation approach, which supports sustainable supply chain management including cooperation between manufacturers and cross-sectorial co-products, and recycling and reuse options in practical applications.

**SAMT** promotes cross-sectorial learning and uptake of the most promising sustainability assessment methods and tools, focusing especially on energy and resource efficiency.

**STYLE** seeks to specify a practical toolkit to be used by future projects and industry sectors to assess the value (in sustainability terms) of new technologies and process modifications aimed at boosting resource and energy efficiency.

## A-14.a Integration of non-technological aspects in calls

Integrating non-technological aspects in calls has the objective of improving the technological solution's effectiveness by integrating the end user and other relevant stakeholders' knowledge and considering the feasible (organisational, societal, environmental) impact right from the beginning. The diagram below shows the non-technological factors that need to be addressed for successful implementation of Industry 4.0 (Dregger, Niehaus, Ittermann, Hirsch-Kreinsen, & ten Hompel, 2016). Similarly, the key non-technological aspects need to be mapped for each innovation programme.



**Figure 13: Interaction of technological and non-technological aspects related to Industry 4.0 (Dregger, Niehaus, Ittermann, Hirsch-Kreinsen, & ten Hompel, 2016)**

To ensure that the relevant non-technological aspects are addressed, a checklist of non-technological aspects was compiled to determine how the relevant aspects should be addressed in calls for proposals. The table below illustrates the non-technological areas and their activities to improve competitiveness and support technological innovation. This is a non-exhaustive catalogue for orientation, listing the main features named by the P4Planet stakeholders.

Category	Potential activities
<b>Framework conditions (Global / European National / Regional)</b>	<p>Proactive (and uniform) European, national, regional, and local frameworks to support innovation acceptance, implementation, and transition (of the green deal):</p> <ul style="list-style-type: none"> <li>Promote uniform norms and regulations regarding energy and waste across EU member states to facilitate cross border business development and efficient infrastructures</li> <li>Identify and overcome regional, national, and European bottlenecks hindering the reuse, recycling, and recirculation of material streams</li> <li>Create the best conditions to accelerate investments to deploy the innovative solutions</li> <li>Stimulate sustainability investments in longer term ROI solutions (e.g. energy savings in energy intensive process industry)</li> <li>Create conditions to attract green investments in Europe</li> <li>Facilitate access to funding and private investments needed beyond company ventures (e.g. to support new energy and recycling concepts within civil society)</li> <li>Formulate (new and politically addressed) key regulations to foster demand for climate-neutral products and support cost-competitiveness</li> <li>Creating market penetration (which PAN European standards are needed or do need to be revised)</li> <li>Creating space for innovative start-ups and scale-up of SMEs that generate solutions for the sustainable European process industry</li> </ul>

Category	Potential activities
	<ul style="list-style-type: none"> <li>• Transparent and harmonised global framework for CO<sub>2</sub> emissions</li> <li>• Ensuring the security of supply (availability of resources, logistics) and needed infrastructure</li> <li>• Ensuring that innovations from one P4Planet sector will be adapted and taken up by another to speed-up the acceleration towards sustainable process industries</li> <li>• Set up of (connected) regional ecosystems of stakeholders from industry, policy, science, vocational education and training (VET), and HE institutions, and civil society (within the H4C)</li> <li>• Considering the impact of process industry transformation on the regional and local level</li> <li>• Considering regional impact (mainly for H4C): economic, policy, framework conditions, labour market, skills level needed, environmental, societal challenges, and demands)</li> <li>• Improve civil society information, acceptance, and commitment</li> </ul>
<b>Market / Consumers</b>	<p>Value chain approach (upstream, midstream, and downstream; creating a market), developing a vision on the implications of consumer products from greener process:</p> <ul style="list-style-type: none"> <li>• Connecting across the value chain: upstream, midstream, and downstream</li> <li>• Support to improve societal acceptance of greener products and to integrate consumer demands for new generation of materials, products, and services</li> <li>• Creation of markets for climate neutral, circular economy products</li> <li>• Developing climate neutral and circular solutions and financing their uptake</li> <li>• Access to resources and deployment</li> <li>• Supporting green industry by public procurement</li> <li>• Piloting new value chain collaboration, organisation, and business models for H4C</li> <li>• Developing and demonstrating new business models for new economic opportunities (e.g. driving circular economy business through digital resource platforms, new business opportunities for value chain or H4C orchestrators, new financial models for servicing the process industry, i.e. for emerging energy carriers)</li> <li>• Creation of lead markets (e.g. on energy reduction, recycled materials as feedstock, industrial symbiosis, energy exchange like carbon to chemicals)</li> <li>• Reflection and integration of consumers' demands</li> <li>• Developing show cases to emphasise the benefits of a greener process industry for the citizens</li> <li>• Integrate business model innovation support tools and processes, as part of the exploitation work package, from the early stages of the project</li> </ul>
<b>Human resources, skills and labour market</b>	<p>New ways to close skills gaps and mismatches, improving the capacity of the process industry to unfold the potential of digitalisation and innovation:</p> <ul style="list-style-type: none"> <li>• Considering impact of the transformation of the process industry on new skills required</li> <li>• Developing new education and training schemes responding to regional, pan European workforce planning within the (digital and ecological) transformation</li> <li>• Recruit and retain talents needed by the companies, how to attract talents to the production industry in Europe (e.g. by attracting more women, high skilled workers)</li> <li>• Transforming of training supply (company internal and external) and the labour market</li> <li>• Creating the innovators of the future: combining technology innovation and business model innovation for the process industry</li> <li>• Cooperation with local/regional education and training providers on the regional/local level (within companies and H4C), bridging with schools and universities, developing new teaching materials</li> <li>• Investments in education and training (division of responsibilities for industry, public VET institutions/universities, and the individuals), new learning models for learning to learn</li> <li>• Change management within the companies to upskill the existing workforce</li> <li>• Integrate experience and competences of the experts of the workplace (operators) within technological innovation development</li> </ul>
<b>Common Tools</b>	<p>Development of a common tool database of good examples, identifying and developing tools of common interest and relevance, stimulating a cross-sector transfer of solutions and foster transferability and exploitation of innovations, stocktaking of innovative solutions all over the P4Planet community (and beyond):</p> <ul style="list-style-type: none"> <li>• Set of life cycle assessment models</li> <li>• Overview of possible (novel) business models for the process industry</li> <li>• Dedicated business model support tools and processes for the process industry</li> <li>• Governance approaches (on the regional level for H4C)</li> <li>• Tools for combining social and technological innovation (e.g. Societal Readiness Levels, social KPIs, etc.)</li> <li>• Overcoming knowledge barriers, exchange of knowledge for new solutions</li> </ul>

Category	Potential activities
	<ul style="list-style-type: none"> <li>• Mapping of existing relevant activities for P4Planet in the sectors and regions</li> <li>• Cross-sectorial transfer of innovative solutions</li> <li>• Stocktaking of similar important activities/programmes/projects beyond P4Planet</li> <li>• Common strategies for specific challenges (e.g. consumer information activities, joint recruitment, and image strategies and tools)</li> </ul>

The text boxes that follow illustrate how non-technological aspects can be addressed.

**Text box 10:** Example for Industrial-Urban Symbiosis

Non-technological aspects considered for the processing of side and waste streams (materials, water, energy, and gas) might include regional stakeholders from policy, economy, civil society, and science setting up a regional ecosystem for the governance of a regional roadmap to improve sustainably the processing of side and waste streams. This should include new market models and consumer behaviour and skills development to unfold the potential of new process technologies within the companies and the region.

**Text box 11:** Example of Greening Technical Vocational Education and Training<sup>124</sup>

Greening Technical Vocational Education and Training (GT VET) for maintenance in the steel shop floor is of high relevance to reduce waste, energy, noise, and emissions. To incentivise workers and apprentices for greener working practices, not only the content but also an effective, efficient, and accepted way of learning/training became relevant. The development of a training module began as a social innovation process by integrating all the relevant stakeholders and future learners. It was evident in the beginning that the planned eLearning module would not be appropriate.

Apprentices and workers instead stressed workplace and action-oriented learning. Ultimately, a common training module was developed that reflected the main requirements of the companies concerning the training modules (energy, waste, noise, and raw material reduction) and the didactical requirements of the learners (starting with basic information and understanding background and coherences but then focusing on practical exercises and projects linked to the concrete workplaces).

The test phase of the training module showed the high engagement of the trainees and also led to new energy saving, emission, and noise reduction practices: through new greener maintenance practices and by changing some elements of the production process (in the sense of workplace innovation).

Besides the integration of the non-technological aspects in the shaping calls, each innovation project will need to identify which non-technological factors are key to the success of the innovation during and after the project. This will inform future calls.

For some innovation programmes, non-technological activities are already included in the programming. For example, common tools for development and dissemination are programmed in various innovation programmes (e.g. in Integration of renewable heat and electricity in A-1.a, in Electrically driven separation in A-4.b, in all Digitalisation programmes in A-13 and various other programmes). The collection and dissemination of the tools is also programmed in the European Community of Practice (A-12.a).

Investments for the integration of non-technological aspects in calls are not estimated separately. The technological investments are typically significantly higher and the non-technological investments are in a range of 1%-5%.

<sup>124</sup> Taken from (Kohlgrüber & Schröder, 2019)

## A-14.b Human resources, skills, and labour market

Within the stakeholder workshops (see Appendix B ) human resources, skills, and labour market issues were high on the agenda. The proactive adjustment of human resources and skills for technological development and implementation is highly important to the success of this roadmap, and for unfolding the technological potential in the sectors, companies, and regions. Technological solutions will only reach their full potential with high-skilled and tailored up- and retrained people.

New ways of cooperation with systems for vocational education and training are needed, up-taking industry skills and qualification demands. This non-technological topic will benefit from the EU funded ERASMUS+ project “Skills Alliance on Industrial Symbiosis (SPIRE-SAIS).” However, this approach must be extended to improve (cross-) sectorial skills in general.

**Text box 12:** Example of ROBOHARSH (human-robot-interface)

Developing a Robotic Workstation in Harsh Environmental Conditions to Improve Safety in the Steel Industry (ROBOHARSH) needed a new allocation of tasks between the human operator and the robot activities. Done in close co-creation between workers and technicians the new division of work did not only improve the acceptance of the end users but also clarified the new required skills. In this case, low skilled, heavy, and dangerous work is substituted by high skilled computer-controlled activities. Based on entirely new practices at their workplace, the operator changed his role from operator to supervisor, taking the interfaces between technology, organisation, and humans into account.

### A-14.b.1 Innovation objectives

Analogous to the European Steel Sector Alliance (ESSA<sup>125</sup>), an innovation programme called “SPIRE-SAIS plus” will be launched to enlarge the SPIRE-SAIS and ESSA Skills Blueprint and to implement a comprehensive skills strategy across all the P4Planet sectors and all the relevant skills demands (not only for industrial symbiosis).

### A-14.b.2 Impacts

This innovation programme’s impact is not quantified separately, but it enables most of the other innovation programmes. The rate of implementation is affected by the availability of sufficiently skilled labour. If this problem is not adequately addressed, the roadmap’s ambitious timeline will be in jeopardy.

Additionally, this innovation programme boosts competitiveness. The skilled labour force and related institutions make European regions more attractive for investments by globally operating companies, but the education system can also attract scholars and talents for the process industries, resulting in a positive feedback loop that will enable Europe to lead the development of sustainable industrial value chains of the future.

### A-14.b.3 Programming

Skills adjustments should ideally have made during the technological development by integrating the experience and knowledge of the workers and end users right from the beginning in the innovation process. This process could also help to specify the concrete training needs (e.g. learning on the job, simulation, traditional training courses). The focus of this non-technological innovation programme includes the following:

- New learning arrangements (digital, cooperation of education systems with companies, e.g. dual system, short-termed implementation of new skills demands/occupations)
- Digitalisation as attracting and recruiting measure (attracting new diverse target groups)

<sup>125</sup> <https://www.estep.eu/essa/>

- Cross-sectorial worker pools (to close mismatches): To better share resources and to promote the development of a pool of workers, employees, and engineers that can fit the needs of various sectors
- Develop monitoring and foresight schemes to proactively identify skills demands and requirements
- Shorten the implementation of industry relevant qualifications in national VET systems, continuously
- Develop and exchange training modules, tools, and the experiences
- Agile education and training systems

New digital skills are especially in focus, as already mentioned in several chapters (e.g. A-13).

As an added value to the SPIRE-SAIS project, all the relevant qualifications of the innovation programmes beyond industrial symbiosis will be in focus. The strategy that is developed will be implemented and rolled out by a European P4Planet skills alliance and consortiums of P4Planet companies and research institutions with national and regional VET providers and institutions on the regional level (where the companies are placed, especially with H4Cs).

Strategies and measures on the national and regional level will help to provide the labour force of the future, dividing the responsibility for it in regional governance or ecosystems (companies, public authorities, job centres, education and training providers, social partners, and civil society organisations within the policy field of education).

This comprehensive skills strategy will be aligned with European programmes like the New Skills Agenda and Marie Skłodowska-Curie actions (MSCA) topics, and on the regional level with H4C (A-12.b), to achieve coordinated skills development with regards to topics and regional needs.

Education is continually relevant, as the educational system should be responsive to changes in the markets and as new innovations will be delivered continuously by the P4Planet programmes.

#### A-14.b.4 Investment needs

Skills are of continuous relevance. A higher investment in the beginning (2020-2025) is necessary to develop and implement innovative solutions, sustainable strategies, measures, structures, and databases, which must be updated and complemented continuously.

A project financing of about €12 million in the first period (for two to three projects focusing on different needs for the human resources and labour market development listed in the previous chapter) is needed, followed by financing of €10 million every 5 years until 2030 and €5 million after 2030 to guarantee the ongoing implementation and activities of the developed solutions and the uptake of new demands.

**Table 40: Investment needs in € million<sup>126</sup>**

Activity	Timing	TRL1-3	4-6	7-8	9	Non-technological	Total
Human resources, skills and labour market	2020-2024					€12	€12
	2024-2030					€10	€10
	2030-2040					2x €5	€10
	2040-2050					2x €5	€10
<b>Total</b>		€0	€0	€0	€0	€42	€42

#### A-14.b.5 Success factors

Beside a strong integration of non-technological aspects in the various technological innovation areas, /programmes, and projects there are different success factors beyond P4Planet:

<sup>126</sup> Highlighted cells indicate the expected scope of innovation within Horizon Europe. This final scope for Horizon Europe is to be determined.

- The **willingness of external stakeholders** (such as municipalities, job centres, education and training providers and institutions, civil society organisations and citizens) to collaborate and close digital skills gaps and mismatches in the labour market.
- Engagement of (national) sector associations and social partners (employer associations and trade unions) as central **communication and dissemination** intersection.
- **Political support measures** by stakeholders and policy makers of the EU and member states level (including European and national vocational education and training institutions).
- Integration and **support of the EC** across different DGs (DG Employment, Research and Innovation, Grow, Connect, Education and Culture, Clima, Regio).
- **Cross-sectorial engagement** and exchange of industry representatives, companies, policy, science, and education.

## Appendix B Process to arrive at this roadmap

This roadmap is the result of intense in-kind contributions from a wide number and variety of A.SPIRE members and from fruitful dialogue with many stakeholders that are relevant to achieve our objectives and to generate synergies and complementarities.

Conversations about the next research and innovation strategy started within SPIRE in 2017 when the mid-term review of H2020 and the partnerships took place. By then, A.SPIRE launched several activities to review its impact and imagine the next generation of European process industry. As from then, the dialogue and collaboration of A.SPIRE members has intensified to develop this 2050 Roadmap.

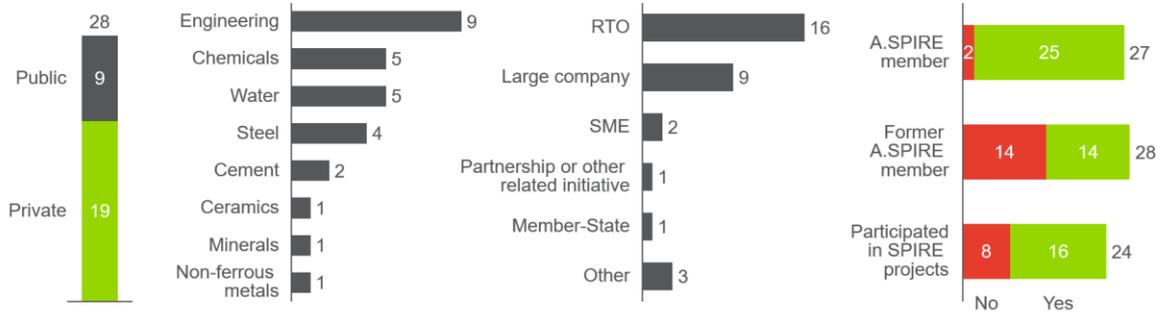
Year	Date	Activity
2017	5 July	Brainstorming event - the future of the Process Industry by 2050
	19-21 September	First European Process Industry Conference gathered over 240 stakeholders to “dream” about the future of our industry and society.
2018	February	Vision Group of representatives from the P4Planet sectors established to define ambitious vision tackling the growing societal challenges of climate change and circular economy. All Industrial Associations of P4Planet sectors, companies and RTOs were involved.
	July	Draft vision shared with A.SPIRE members for internal consultation
	20 September	Draft P4Planet 2050 Vision released outlining new value proposition and three ambitions.
	2 October	P4Planet Vision Workshop gathered over 120 stakeholders to discuss and validate the draft vision.
	29 October	Joint workshop during INDTECH Conference with representatives from P4Planet, FoF and EeB partnerships, DG RTD, MS and the industry
	28 November	Dinner debate in the European Parliament with A.SPIRE members, high- level representatives from DG RTD, other stakeholders and MeP Dan Nica designated as the HEU Rapporteur.
	13 December	P4Planet workshop at COP24. EP, EC, MS and NGO high-level representatives discussed the Vision with the A.SPIRE President and Cefic Director-General.
2019	Q1	7 working groups (WG) installed to develop the roadmap, collectively counting over 175 people. Navigant, a Guidehouse company, selected for support.
	26 March	Kick-off workshop for roadmap development, involving all WG members of A.SPIRE Advisory Group.
	29 May	IRIAG workshop with main representatives of P4Planet sectors and innovation community to identify links across WGs and ensure coherence and consistency of the roadmap
	11 September	P4Planet WG Day gathers all WGs representatives and BoD members to boost the level of innovation and ambition of the roadmap. The booklet of our 2050 roadmap is shared with key stakeholders such as the EC, MS, regions, new sectors or parties interested in our Vision et al. Online consultation was open to all our members.
	22 November	P4Planet 2050 roadmap draft is released, and online consultation is launched for stakeholders to provide feedback
	3 December	P4Planet Stakeholders’ workshop will gather more than 140 stakeholders to openly discuss about our roadmap and identify GAPs, and potential for synergies across sectors, partnerships and regions.
	December	Roadmap discussed with A.SPIRE Advisory Group and BoD.
2020	February	Release of roadmap pre-final version

The next sections outline the quantitative input from the online stakeholder consultation and the stakeholder workshop.

### B-1 Online stakeholder consultation

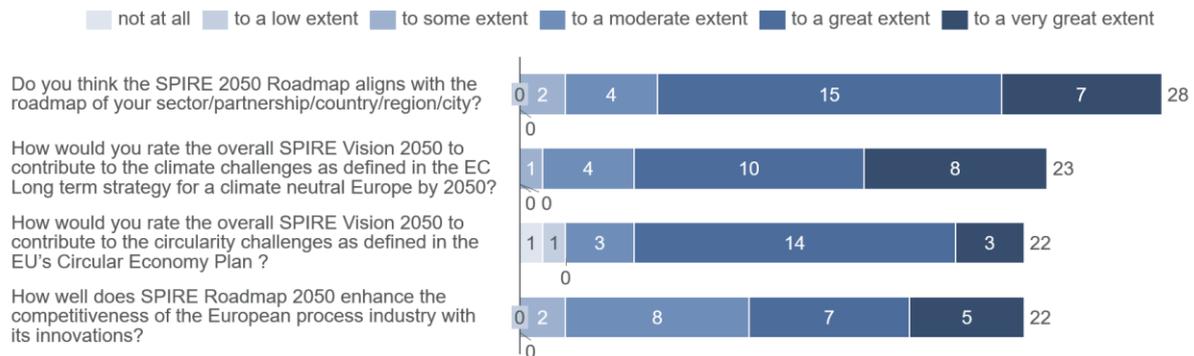
A range of stakeholders were invited to provide feedback on the preliminary draft roadmap in November 2019. The chart that follows depicts the participants of this online consultation.

### Participants online consultation



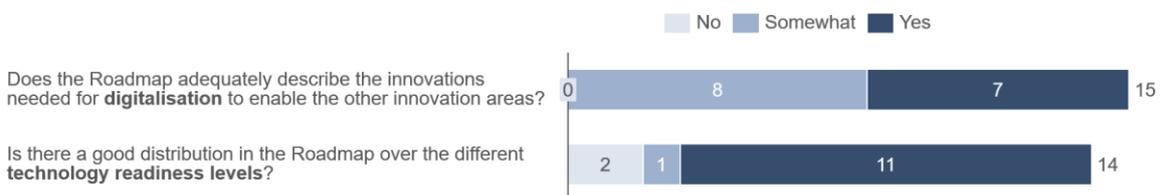
Participant feedback showed that the draft roadmap was well-aligned with other roadmaps, and with policy objectives related to GHG emissions. On circular economy and competitiveness, it was reasonably well-aligned. Based on this feedback the roadmap has been strengthened in the area of circular economy and competitiveness.

### Alignment of the SPIRE 2050 Roadmap



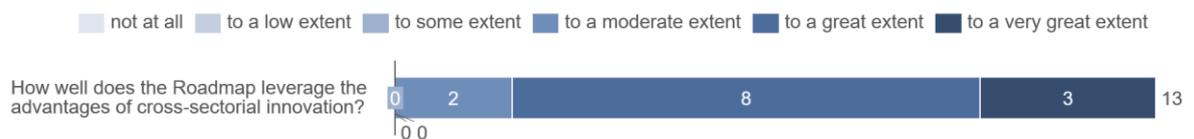
The stakeholder feedback also pointed out that the description of digitalisation and the enabling effect on other innovation areas could be improved. Based on this feedback the role of digitalisation in the other innovation programmes was elaborated more. Most participants thought the distribution of TRLs (lower versus higher-TRL) in the draft roadmap was well-balanced.

### Digitalisation & TRL distribution



Stakeholders thought that benefits of cross-sectoriality were well-leveraged in the roadmap but could be leveraged even better.

### Cross-sectoriality

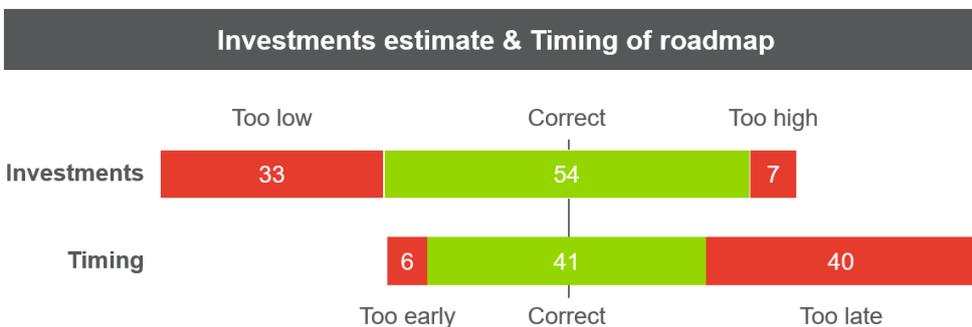


## B-2 Stakeholder workshop

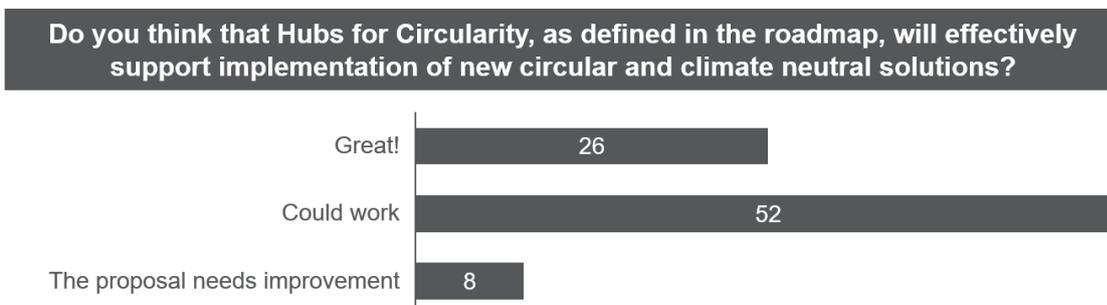
On 3 December 2019, A.SPIRE hosted a stakeholder workshop to discuss and collect feedback on the draft roadmap. Televoting was used to collect input during the opening of the workshop. Not all participants answered all questions, but the results do offer insights. The chart below shows that a wide range of different sectors and stakeholders attended the workshop.



A substantial share of participants thought that the investment estimate in the draft roadmap (which was around €17 billion in total at that time, based on incomplete data and excluding a number of innovation programmes) was on the low end. Note that the final investment estimate was indeed higher after finalising the roadmap (i.e. €33.8 billion). The timing of the innovation programmes was considered too late by a substantial share of respondents. Based on this insight the innovation programmes were reconsidered to accelerate the pace of innovation.



Most participants thought that H4C could work to support implementation of new circular and climate neutral solutions. The subsequent sessions in the workshop showed that many stakeholders thought that it was not described concretely enough how P4Planet would support the development of H4C. Therefore, H4C sections were detailed more in the roadmap.



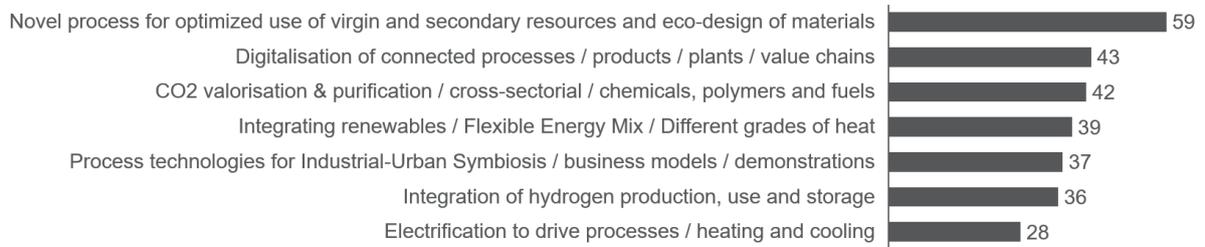
The stakeholders considered the cross-sectorial cooperation the most important benefit of P4Planet, followed by the knowledge sharing, joint developing of a strategy, and structured dialogue with the public authorities about the innovation ecosystem.

**What is the most important benefit an organization such as SPIRE has?**



The stakeholders showed interest in all innovation areas in the roadmap.

**Which innovation area(s) would you put your money in?**



## Appendix C TRL definitions

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Technology readiness 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 (EC, 2014b).

# Appendix D Glossary of terms and abbreviations

## Glossary

<b>A.SPIRE</b>	A.SPIRE is the European Association which is committed to manage and implement SPIRE and P4Planet
<b>H4C / Hub for Circularity</b>	A cluster of interconnected industrial (large companies and SMEs) and/or public facilities within a given geographical area, which collectively achieve a demonstrable level of circularity and climate neutrality in their use of resources (including feedstock as well as energy and water) whilst boosting global competitiveness of the EU Process Industry and sustainable growth.
<b>Resources</b>	The energy and feedstock required to produce materials
<b>Feedstocks</b>	The raw materials that are used as input in the process industries to produce materials (e.g. iron ore or naphtha).
<b>Materials</b>	The intermediary products developed by the process industries (e.g. crude steel)
<b>GHG emission-free energy</b>	Energy that does not result in any GHG emissions into the atmosphere. This includes for example wind or solar power, biomass, solar heat, geothermal heat, green or blue hydrogen, or fossil fuel-based power generation with CCS. Upstream emissions (e.g. from production of assets) are not considered as in international climate conventions.
<b>Recycling, upcycling and downcycling</b>	In this roadmap recycling refers to upcycling (keeping a resource in the same loop, for example the recycling of aluminium with the same quality) as well as downcycling (using a material in a lower value application, for example the use of ground bricks on tennis courts). The word recycling does not refer to energy recovery (burning the waste to generate heat and/or electricity). This choice is made as the distinction between upcycling and downcycling is not always clear cut. The goal is to recycle towards high value applications where possible (upcycling).

## Abbreviations

<b>AGS</b>	Aerated granular sludge	<b>LOHC</b>	Liquid organic hydrogen carrier
<b>B2T</b>	Business-to-territory	<b>MEA</b>	Monoethanolamine
<b>BF/BOF</b>	Blast Furnace/Basic Oxygen Furnace	<b>MSW</b>	Municipal solid waste
<b>CAPEX</b>	Capital expenses	<b>MVR</b>	Mechanical vapour recompression
<b>CCS</b>	Carbon Capture and Sequestration	<b>NIS</b>	National Innovation System
<b>CCU</b>	Carbon Capture and Utilisation	<b>OPEX</b>	Operational expenses
<b>CO</b>	Carbon Monoxide	<b>P</b>	Phosphorus
<b>CO<sub>2</sub></b>	Carbon Dioxide	<b>P4Planet</b>	Processes4Planet
<b>CPU</b>	Capture and purification unit	<b>PAT</b>	Process analytical technologies
<b>CSA</b>	Coordinated Support Action	<b>PCI</b>	Pulverized coal injection
<b>DAC</b>	Direct air capture	<b>PEC</b>	Photoelectrocatalysis
<b>DRI</b>	Direct reduced iron	<b>PEM</b>	Polymer Electrolyte Membrane
<b>DTI</b>	Digital transformation of industries	<b>PET</b>	Polyethylene terephthalate
<b>EAF</b>	Electric arc furnace	<b>PFC</b>	Perfluorocarbon
<b>EBITDA</b>	Earnings before interest, taxes, depreciation and amortization	<b>PPC</b>	Polypropylene carbonate
<b>EC</b>	European Commission	<b>PV</b>	Photovoltaic
<b>EEA</b>	European Environment Agency	<b>PVC</b>	Polyvinyl chloride
<b>EIT</b>	European Institute of Innovation & Technology	<b>R&amp;D</b>	Research and development
<b>ETS</b>	Emissions Trading System	<b>RCF</b>	Recycled concrete fines
<b>EU</b>	European Union	<b>RDI</b>	Research, Development and Innovation
<b>EV</b>	Electric vehicle	<b>REI</b>	Resource efficiency indicator
<b>FDCA</b>	2,5-Furandicarboxylic acid	<b>RTO</b>	Research & Technology Organisation
<b>FOAK</b>	First-of-a-kind	<b>SDG</b>	Sustainable Development Goal
<b>GDP</b>	Gross Domestic Product	<b>SET Plan</b>	Strategic Energy Technology Plan
<b>GHG</b>	Greenhouse gas	<b>SME</b>	Small and medium-sized enterprises
<b>GVA</b>	Gross Value Added	<b>SMR</b>	Steam methane reforming
<b>H<sub>2</sub></b>	Hydrogen	<b>SPIRE</b>	Sustainable Process Industry through Resource and Energy Efficiency
<b>HFO</b>	Hydro fluoro-olefin	<b>TEA</b>	Techno-Economic Assessment
<b>HMF</b>	Hydroxymethylfurfural	<b>TRL</b>	Technology Readiness Level
<b>IT</b>	Information technology	<b>TSO</b>	Transmission system operator
<b>I-US</b>	Industrial-Urban Symbiosis	<b>VET</b>	Vocational education and training
<b>KIC</b>	Knowledge and Innovation Community	<b>WWRF</b>	Wastewater resource recovery facilities
<b>KPI</b>	Key performance indicator	<b>WWTP</b>	Wastewater treatment plant

## Appendix E Analytical approach

### E-1 Greenhouse gas emissions

The roadmap uses the below CO<sub>2</sub> emissions for the quantification of impacts. The values are all in MtCO<sub>2</sub> and include only CO<sub>2</sub> and no other GHGs.

Sector	Fossil fuel combustion emissions	Process emissions	Electricity-related emissions	Total emissions
<b>Cement</b>	40.8	61.2	5.3	107.3
<b>Steel</b>	190.0	0.0	18.0	208.0
<b>Chemicals</b>	68 <sup>127</sup>	62.0	50	180
<b>Ceramics</b>	16.1	3.9	4.5	24.5
<b>Non-ferrous metals</b>	9.6	5.3	20.4	35.4
<b>Minerals</b>	5.9	13.5	3.5	22.9
<b>Water</b>	0.0	0.0	5.7	5.7
<b>Pulp &amp; Paper</b>	32	0	10	42
<b>Refining</b>	110	0	14	124
<b>Total P4Planet</b>	<b>473</b>	<b>145</b>	<b>131</b>	<b>749</b>

Various numbers circulate when it comes to the emissions of industrial sectors. The numbers have different scopes and data sources and are used for different purposes. For the purpose of this roadmap, transparent numbers from public and credible sources is essential. Where possible, figures provided by the sector associations are used. Process emissions are defined as those emissions that cannot be mitigated by means of a fuel shift. This means that use of fossil fuel as a feedstock (for example, the coal that is used as reductant in steel production) is included under the fossil fuel combustion emissions.<sup>128</sup>

Sector	Approach	Sources
<b>Cement</b>	<ul style="list-style-type: none"> <li>Direct emissions for the cement sector (102 MtCO<sub>2</sub> in 2017) are taken from GNR – GCCA, 60% of which are assumed to be process emissions based on Cembureau.</li> <li>Electricity consumption by the EU cement sector (65 PJ in 2017) is derived from GNR – GCCA.</li> <li>The average EU emission factor of 82 tCO<sub>2</sub>/TJ is used to convert electricity consumption into GHG emissions.</li> </ul>	(CEMBUREAU, 2013) (Global Concrete and Cement Association, 2017) (EEA, 2019)
<b>Steel</b>	<ul style="list-style-type: none"> <li>Direct steel emissions (190 MtCO<sub>2</sub> in 2015) are retrieved from VUB/IES.</li> <li>Electricity-related emissions (18 MtCO<sub>2</sub>e) are retrieved from Material Economics.</li> <li>Note that these values differ slightly from the numbers in the Eurofer roadmap but are used to be consistent with the other sectors.</li> </ul>	(Wyns, Khandekar, & Robson, 2018) (Material Economics, 2019) (EUROFER, 2019)
<b>Chemicals</b>	<ul style="list-style-type: none"> <li>Direct emissions from the chemical industry (123.8 MtCO<sub>2</sub>e in 2017) are retrieved from EEA data and validated with Cefic numbers.</li> <li>Electricity consumption (662 PJ in 2017) is retrieved from Eurostat energy balances.</li> <li>The average EU emission factor of 82 tCO<sub>2</sub>/TJ is used to convert electricity consumption into GHG emissions.</li> </ul>	(Cefic, 2019) (EEA, 2019) (Eurostat, 2020b)
<b>Ceramics</b>	<ul style="list-style-type: none"> <li>Direct emissions (20 MtCO<sub>2</sub>e in 2017) are retrieved from Cerame-Unie</li> <li>Of this, process emissions are 20% according to the sector roadmap from 2012 (16% out of 82% direct emissions).</li> <li>Electricity-related emissions from the ceramics sector (4.5 MtCO<sub>2</sub>) are retrieved from Cerame-Unie</li> </ul>	(Cerame-Unie, 2020) (Cerame-Unie, 2012)

<sup>127</sup> The emissions associated with the current production of hydrogen, ammonia and methanol are estimated to be around 30% of the chemical industries' current emissions (based on (Ecofys, 2009)). Part of these emissions, which are dependent on the fuel used, are typically considered process emissions.

<sup>128</sup> For simplicity where relevant the feedstock related emissions are not subtracted from total fossil fuel-related emissions when the impact is estimated as a % reduction from the total emissions.

Sector	Approach	Sources
<b>Non-ferrous metals</b>	<ul style="list-style-type: none"> <li>Direct emissions from non-ferrous metals are taken from EEA: 9.6 MtCO<sub>2</sub> fossil fuel-related CO<sub>2</sub> emissions and 5.3 MtCO<sub>2</sub> process emissions in 2017<sup>129</sup></li> <li>Electricity consumption for non-ferrous metals is retrieved from Eurostat energy balances (249 PJ in 2017)</li> <li>Emissions calculated using the average EU emission factor of 82 tCO<sub>2</sub>/TJ from EEA.</li> </ul>	(EEA, 2019) (EEA, 2019) (Eurostat, 2019b)
<b>Minerals</b>	<ul style="list-style-type: none"> <li>Direct emissions for the minerals sector are dominated by lime production, which is the most energy-intensive activity in the sector.</li> <li>Direct emissions from lime production (19.4 MtCO<sub>2</sub>e in 2015) are retrieved from VUB/IES.</li> <li>Direct emissions from lime are divided into fossil-fuel and process emissions based on the breakdown from the sector roadmap (i.e. 68% process emissions, 30% fossil fuel emissions, 2% electricity emissions).</li> <li>Electricity consumption for industrial minerals is derived from Eurostat energy balances for "Mining and quarrying" (70 PJ in 2017) by assuming that 60% of this electricity is consumed to produce industrial minerals.</li> <li>The 60% assumption is based on the share of industrial minerals by weight in the total production volume according to Eurostat in the period 2015-2017.</li> <li>The average EU emission factor of 82 tCO<sub>2</sub>/TJ is used to convert electricity consumption into GHG emissions based on EEA.</li> </ul>	(Wyns, Khandekar, & Robson, 2018) (Stork, Meindertma, Overgaag, & Neelis, 2014) (Eurostat, 2019b) (EEA, 2019)
<b>Water</b>	<ul style="list-style-type: none"> <li>Direct emissions from the water sector (0 MtCO<sub>2</sub> in 2017) are retrieved from Eurostat (Industrial wastewater).</li> <li>Electricity consumption (70 PJ in 2016) is also taken from Eurostat (Sewerage, waste management, remediation activities). Note that the water sector is larger, and includes water collection, treatment and supply. However, here we choose a narrower scope where the innovations in this roadmap are most relevant.</li> <li>Average EU emission factor of 82 tCO<sub>2</sub>/TJ is used to convert electricity consumption into GHG emissions (EEA, 2019).</li> </ul>	(Eurostat, 2019b) (EEA, 2019).
<b>Refining</b>		
<b>Pulp &amp; paper</b>		

## E-2 Waste

The table below summarises generated waste in Europe, and whether or how they are included in this roadmap. The table is based on 2016 data, using Eurostat's env\_wasgen database. The description of the waste categories is copied from (Eurostat, 2013).

Category	Waste generated (Mt)	Definition of the category	Included?
<b>Spent solvents</b>	2.35	These are hydrocarbons, fluorocarbons, chlorinated carbons; organic halogenated, non-halogenated solvents, including organic washing liquids; and organic fluorinated refrigerants. They are used in chemical industries as reaction agent and in extraction processes, cleaning processes in mechanical engineering and surface treatment and appear almost exclusively in the manufacture of chemicals, chemical products, basic pharmaceutical products and preparations, and rubber and plastic products (item 9 of Section 8 of Annex I of the Waste Statistics Regulation). To a lesser extent, this type of waste can also be generated during the fabrication of metal products and during	Yes

<sup>129</sup> Note that this differs from the numbers presented in (Wyns & Khandekar, 2019) because here only CO<sub>2</sub> emissions are included, and more recent data is retrieved from Eurostat, showing increased electricity consumption

Category	Waste generated (Mt)	Definition of the category	Included?
		recycling. Separately collected fractions of spent solvents can be generated by almost all economic activities, including private households.	
<b>Acid, alkaline and saline wastes</b>	5.77	These are inorganic acids (like hydrochloridric, sulphuric, phosphoric, nitric acids); alkaline like calcium ammonium, sodium hydroxide and inorganic salts mainly from the manufacturing of acids or alkaline and salt slags or solid slags. They mainly originate from surface treatment in metallurgy and equipments sectors and inorganic chemical processes. In general, acids and alkaline are hazardous except lime mud and degreasing waste without dangerous substances (like oil, heavy metals or cyanides). Saline waste is dangerous when containing dangerous substances like heavy metals, arsenic or oil.	Yes
<b>Used oils</b>	4.24	These wastes are mineral-based, synthetic oils and biodegradable engine oils. This category includes engine, gear, hydraulic and lubricating oils, oils for insulation and heat transmission; emulsions from metal surface shaping and residues from tank cleaning. They originate both from the refining process and from the mechanical engineering and maintenance of vehicles in all sectors. Most used oils are collected and treated by a small number of collectors and treatment facilities. Because of the hazards involved, these facilities are monitored and data coverage is relatively good with regard to the quantities collected. Problems of comparability arise when used oils are mixed with other substances such as emulsions for metal surface shaping and residues from tank cleaning. All used oils are hazardous.	Yes
<b>Chemical wastes</b>	16.99	These are solid or liquid spent chemical catalysts; offspecification products and wastes like agro-chemicals, medicines, paint, dyestuff, pigments, varnish, inks and adhesives, including related sludges; chemical preparation waste like preservatives, brake and antifreeze fluids, waste chemicals; tars and carbonaceous waste like acid tars, bitumen, carbon anodes, tar and carbon waste; fuels, emulsions, sludges containing oil, like bilge oil, waste fuels oil, diesel, petrol, waste from oil water separator; aqueous rinsing and washing liquids, aqueous mother liquors; spent filtration and adsorbent material like activated carbon, filter cakes, ion exchangers. They mainly originate from the chemical industry and from various industrial branches producing and using chemical products. They are hazardous when containing toxic chemical compounds, oil, heavy metals or other dangerous substances.	Yes
<b>Industrial effluent sludges</b>	13.11	These wastes are sludges and solid residues from industrial wastewater treatment including external/physical treatment; solid and liquid wastes from soil and groundwater remediation; sludges from boiler cleaning; wastes from cooling water preparation and cooling columns; and drilling mud. Wastewater treatment takes place in many industrial manufacturing sectors. Industrial effluent sludges are hazardous when containing oil and heavy metals. A problem of comparability among countries might arise when LUs are used as statistical units, as the waste water treatment processes might not be geographically isolated and the sludges might not be attached to the primary activity.	No <sup>130</sup>
<b>Sludges and liquid wastes from waste treatment</b>	9.67	These wastes comprise different types of sludges and liquid wastes from waste treatment facilities. They include wastes from the physico/ chemical treatment of hazardous wastes, liquids and sludges from the anaerobic treatment of waste, landfill leachate and effluent treatment sludges from oil regeneration. Sludges and liquid wastes from waste treatment are hazardous and non-hazardous.	Yes
<b>Healthcare and biological waste</b>	2.02	These wastes comprise only biological waste from the healthcare of animals and humans. They mainly originate from clinics and hospitals, including veterinary activities, but can also be produced by industries generating healthcare and biological products as production wastes and in lower quantities by all industrial sectors as they all have first-aid kits. Healthcare and biological waste is hazardous when infectious.	Yes
<b>Metallic wastes, ferrous</b>	74.97	These wastes are ferrous metals (iron, steel) and alloys. They include wastes like mill scales from the iron and steel industry, metal filings, turnings and particles from metal processing, construction and demolition waste, discarded moulds from ceramic production, metals from mechanical treatment and shredding of waste, and metals removed from waste incineration slag. The ferrous metal wastes covered by category 06.1 are non-hazardous.	Yes
<b>Metallic wastes, non-ferrous</b>	8.94	These wastes are non-ferrous metals (aluminium, copper zinc, lead, tin, etc.) and alloys. They include wastes like metal filings, turnings and particles from the processing of non-ferrous metals, hard zinc from galvanising processes, cables, construction and demolition waste, components from ELV dismantling and metals from the mechanical treatment and shredding of waste. Non-ferrous metal wastes covered by category 06.2 are non-hazardous.	Yes
<b>Metallic wastes, mixed ferrous and non-ferrous</b>	14.67	These wastes are mixtures of ferrous and non-ferrous metals and alloys or unspecified metal wastes. They include mixed metals from construction and demolition, mixed metals from separate collection (e.g. metal packaging) and unspecified metal waste from the agricultural sector. Mixed metal wastes covered by category 06.3 are nonhazardous.	Yes

<sup>130</sup> Around 1/3 of Industrial effluent sludges ( $\pm 13$  Mton/year) is currently landfilled. It includes sludges and solid residues from industrial wastewater treatment (0).

Category	Waste generated (Mt)	Definition of the category	Included?
<b>Glass wastes</b>	19.00	These wastes can be waste from glass packaging; glass waste from the production of glass and glass products; and waste glass from sorting and recycling processes. Glass waste occurs in a small number of production sectors (construction and demolition, recycling of end-of-life vehicles and electrical, electronic equipment and glass manufacturing) and also as a result of the separate sorting by businesses and households, but can be generated by all sectors as consumption residues or packaging. Glass wastes are hazardous in case of glass powder (particle size relevant) and when containing heavy metals.	No (not a P4Planet sector)
<b>Paper and cardboard wastes</b>	50.66	These wastes are paper and cardboard from sorting and separate sorting by businesses and households. This category includes fibre, filler and coating rejects from pulp, paper and cardboard production. These wastes are largely generated by three activities: separate collection, mechanical treatment of waste and pulp, and paper and cardboard production and processing. All paper and cardboard wastes are non-hazardous.	Not separately <sup>131</sup>
<b>Rubber wastes</b>	3.37	These wastes are only end-of-life tyres which come from the maintenance of vehicles, and end-of-life vehicles. All rubber wastes are non-hazardous. They can be generated in all sectors.	Yes
<b>Plastic wastes</b>	17.59	These are plastic packaging; plastic waste from plastic production and machining of plastics; plastic waste from sorting and preparation processes; and separately collected plastic waste. They originate from all sectors as packaging waste, from sectors producing plastic products and from separate sorting by businesses and households. All plastic wastes are nonhazardous. A distinction should be made between plastic waste and mixed packaging (mixed and undifferentiated materials, items 36/37).	Yes
<b>Wood wastes</b>	54.74	These wastes are wooden packaging, sawdust, shavings, cuttings, waste bark, cork and wood from the production of pulp and paper; wood from the construction and demolition of buildings; and separately collected wood waste. They mainly originate from wood processing, the pulp and paper industry and the demolition of buildings but can occur in all sectors in lower quantities due to wooden packaging. Wood wastes are hazardous when containing hazardous substances like mercury or tar-based wood preservatives.	Yes
<b>Textile wastes</b>	2.19	These wastes are textile and leather waste; textile packaging; worn clothes and used textiles; waste from fibre preparation and processing; waste tanned leather; and separately collected textile and leather waste. They originate from only a small number of activities: the leather and fur industry, the textile industry, the mechanical treatment of waste and separate collection. All textile wastes are non-hazardous.	Yes
<b>Waste containing PCB</b>	0.04	These wastes are oil-containing PCB (e.g. hydraulic oil, insulation and heat transmission oil from transformers); PCB containing components from post-consumer products; construction and demolition wastes containing PCB (e.g. sealants resin-based floorings). They originate from the construction and demolition sector, the mechanical treatment of waste, the manufacture of computer, electronic and optical products, and in lower quantities by all sectors still discarding PCB-containing components (e.g. batteries). All wastes containing PCB are hazardous.	No (too small, environmental issue rather than circularity issue)
<b>Discarded equipment</b>	5.97	These wastes are discarded electrical and electronic equipment (e.g. small and large household equipment, IT equipment, electric tools) and fluorescent tubes. Batteries and end-of-life vehicles are excluded from this category as they should be reported in items 28/29 and 30/31, respectively. They can be generated by all economic sectors and need to be separately collected in accordance with EU directives on electrical and electronic equipment	Yes
<b>Discarded vehicles</b>	9.91	These are all kinds of end-of-life vehicles. They originate from businesses and households. Discarded vehicles are hazardous when containing dangerous substances (e.g. cooling liquids, engine oil or fuel, chlorofluorocarbons from air conditioning).	No <sup>132</sup>
<b>Batteries and accumulators wastes</b>	1.92	These wastes mainly originate from households although they can be produced in lower quantities by all sectors. Batteries and accumulators are hazardous when containing dangerous substances; e.g. nickel, cadmium, mercury, lead and unsorted batteries and accumulators' wastes.	No <sup>133</sup>
<b>Animal and mixed food wastes</b>	26.00	These wastes are animal and mixed wastes from food preparation and products, including sludges from washing and cleaning; separately collected biodegradable kitchen and canteen waste, and edible oils and fats. They originate from food preparation and production (agriculture and manufacture of food and food products) and from separate collection. Animal and mixed waste of food preparation and products are non-hazardous.	No (BBI consortium)
<b>Vegetal wastes</b>	55.30	These wastes are vegetal wastes from food preparation and products, including sludges from washing and cleaning, materials unsuitable for consumption and green wastes. They originate from food and beverage production, and from agriculture, horticulture and forestry. Vegetal wastes are non-hazardous.	
<b>Animal faeces,</b>	13.98	These wastes are slurry and manure including spoiled straw. They originate from agriculture. Animal faeces, urine and manure are non-hazardous.	

<sup>131</sup> Recycling of ink sludge is covered under "chemical waste" and separating off plastic layers / recycling of the hydrocarbons currently not yet recycled is covered under "chemical recycling"

<sup>132</sup> No key innovation needs identified at the level of the process industry

<sup>133</sup> Battery recycling is mainly organized by the battery manufacturers, without looping back into the process industry

Category	Waste generated (Mt)	Definition of the category	Included?
<b>urine and manure</b>			
<b>Household and similar wastes</b>	167.1	These wastes are mixed municipal waste, bulky waste, street-cleaning waste like packaging, kitchen waste, and household equipment except separately collected fractions. They originate mainly from households but can also be generated by all sectors in canteens and offices as consumption residues. Household and similar wastes are non-hazardous.	Not specifically <sup>134</sup>
<b>Mixed and undifferentiated materials</b>	44.68	These are unspecified and mixed waste without any general waste source. This category covers not only mixed packaging but also mainly residual categories from different branches of industry (food production, textile industry, combustion plants, surface treatment of metals and plastics, etc.). These residual categories are often used for nation-specific waste codes. Mixed and undifferentiated materials are hazardous when containing heavy metals or organic pollutants.	
<b>Sorting residues</b>	95.23	These wastes are sorting residues from mechanical sorting processes for waste; combustible waste (refuse derived fuel); and non-composted fractions of biodegradable waste. They mainly originate from waste treatment and separate collection. Sorting residues from demolition activities are excluded. They are hazardous when containing heavy metals or organic pollutants.	
<b>Common sludges</b>	20.71	These are wastewater treatment sludges from municipal sewerage water and organic sludges from food preparation and processing. They mainly originate from households and industrial branches with organic wastewater (mainly pulp and paper as well as food preparation and processing). They can also occur in wastewater treatment plants or in the anaerobic treatment of waste. All common sludges are non-hazardous. Comparability can be problematic between countries using different statistical units as they will not assign the waste to the same economic sector.	Not specifically (already mentioned under "Sludges and liquid wastes from waste treatment")
<b>Mineral waste from construction and demolition</b>	344.72	These are concrete, bricks, and gypsum waste; insulation materials; mixed construction wastes containing glass, plastics and wood; and waste hydrocarbonised road-surfacing material. They originate from construction and demolition activities. They are hazardous when containing organic pollutants.	Yes
<b>Other mineral wastes</b>	703.82	These are waste gravel, crushed rocks, waste sand and clays, muds and tailings from extractive industries; blasting materials, grinding bodies, sludges, particulates and dust from the manufacture of glass, ceramic goods and cement; casting cores and moulds from the casting of ferrous and non-ferrous pieces; linings and refractories from thermal processes; and asbestos materials from all branches (asbestos processing, cement, brake pads etc.). They are hazardous when containing asbestos, oil or heavy metals.	Yes
<b>Combustion wastes</b>	117.72	These are wastes from flue gas cleaning (desulphurization sludges, filter dust and cakes, fly ashes); slags, drosses, skimmings, boiler dusts, and ashes from thermal processes. They originate from any thermal and combustion process (power stations and other combustion plants, thermal metallurgy, casting of ferrous and non-ferrous pieces, manufacture of glass and glass products, manufacture of ceramic goods, bricks, tiles and construction products, manufacture of cement, lime and plaster). Combustion wastes are hazardous when containing organic pollutants, oil and heavy metals.	Yes
<b>Soils</b>	494.06	These wastes are soils and stones that originate mainly from construction activities, the excavation of contaminated sites and soil remediation. They are hazardous when containing organic pollutants, heavy metals or oil.	Not specifically (innovation needs are described under the other waste categories)
<b>Dredging spoils</b>	90.3	These are wastes that mainly come from the construction and maintenance of water projects, dredging and subsurface work. They are hazardous when containing heavy metals or organic pollutants.	
<b>Solidified, stabilised or vitrified wastes, Mineral waste from waste</b>	46.03 <sup>135</sup>	These are wastes from the incineration and pyrolysis of waste (bottom ash, slag, fly ash, sands from fluidised beds, boiler dust, filter cake from gas treatment); mineral fraction from the mechanical treatment of waste; and wastes from treatment processes that solidify waste, stabilise or neutralise dangerous substances by a chemical reaction or vitrify waste in a thermal process. The wastes are hazardous when containing organic pollutants or heavy metals, or when only partly stabilised.	Yes

<sup>134</sup> Innovations required to enhance recycling of these streams are already covered in the description of the other waste streams. Recovery of ceramics and aluminium has specifically been mentioned by working group members. H4C can help by sharing experiences and by optimizing the symbiosis between urban and industrial waste treatment thus optimizing waste treatment in a cluster. Increasing focus on upcycling might have an increasing impact on the amount of "sorting residues" (stricter separation due to higher purity needs), while innovative separation processes would aim to reduce the amount of "sorting residues". 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)

<sup>135</sup> Quantity based on "Mineral wastes from waste treatment and stabilised wastes" in Eurostat.

Category	Waste generated (Mt)	Definition of the category	Included?
treatment and stabilised wastes			

### E-3 Programming of innovation

Innovation is programmed as soon as possible, without accounting for market readiness, as the market readiness is dependent on economics or policy framework (which are not in the scope of this roadmap). This also implies that technologies are used as soon as they reach a reasonable level of efficiency and scalability, and technologies are not deployed until efficient and scalable. The roadmap only includes innovation that reaches TRL9 before 2050 (otherwise it cannot contribute towards the ambitions).

The programming is completed across time and level of development. The time intervals 2020-2024, 2024-2030, 2030-2040, and 2040-2050 are selected to align with key milestone years. Four technology readiness level categories are used for the level of development. This aggregation simplifies the exercise in practice because multiple TRLs can often be progressed within one project. Additionally, non-technological activities are programmed (that cannot be categorised in the content below).

As risk of failure is inherent with innovation projects, more low-TRL projects are programmed than high-TRL projects. To be somewhat consistent, typical ranges for conversion rates are defined for each TRL category. In most cases, the higher end of the range for conversion rates are used in the innovation programmes. The rationale for this is that through P4Planet's coordinated approach the conversion rate can be increased compared to typical industry averages.

To program consistently over time typical progression times are considered. They are depicted in the table below as well. For comparison, the VCI roadmap for the chemical industry in Germany assumes 7 years per TRL (for TRL6-9) in its 61% GHG emission reduction technology path (DECHEMA & FutureCamp, 2019). Their more ambitious GHG neutral 2050 path assumes a more rapid technology development.

	TRL1-3	TRL4-6	TRL7-8	TRL9
<b>Description</b>	Research and development	Towards a pilot	Demonstration	First of a kind (FOAK) demonstration
<b>Conversion rate</b>	10-30% to next category	25-50% to next category	50-100% to next category	
<b>Progression time</b>	3-4 years to next category	3-4 years to next category	2-5 years to next category	

### E-4 Quantification of impact

In this roadmap, for most innovation programmes the impact is estimated in terms of GHG emissions, waste reduction, and competitiveness.

For GHG emissions and waste, the impact estimation captures the potential impact in terms of addressable GHG emissions or waste today. This means that the GHG emissions or waste volumes are not projected towards the future. Doing that would include many uncertainties and assumptions, making it more difficult to interpret the results.

A key assumption is that electricity is produced in a climate neutral fashion in 2050. Many projections (including those from the EC) expect the emission factor to decrease, but not reach zero in 2050. However, these projections do not achieve a climate neutral society in 2050, and

therefore the 1.5 °C scenarios presented in the EC long-term strategy are used to inform the emission factor (EC, 2018). These scenarios have a similar ambition as P4Planet and show an emission factor of zero in 2050. As electricity is a GHG emission-free energy carrier in the impact estimations, electrification is highly effective in lowering emissions. If the power sector does not become climate neutral such impacts will not be achieved. As the ambition is set for 2050, we also use the emission factor of zero for electricity in 2030, anticipating the 2050 emission factor.

For 2050, the GHG emissions and waste impacts represents the maximum technical potential of the mature technology if applied in all potential applications. For 2030, the GHG emissions and waste impacts are estimated on a high level using simple assumptions. Technologies that are at TRL9 before 2024 are assumed to be deployed afterwards and realise 10% of the 2050 impact by 2030. For technologies that are at TRL9 after 2024 and before 2030, only the first of its kind plant is included in the impact estimation. It is typically impossible to properly estimate the impact of an installation that has not been demonstrated yet and the estimations are often more an order of magnitude than a factual representation of the impact of a single installation.

The impact on competitiveness is more difficult to define in a single number. For the purpose of this roadmap, competitiveness is quantified where possible by estimating at what energy price a technology is competitive with the current technology.

Where impacts could not be quantified a qualitative description of the impacts is provided.

## E-5 Quantification of investment needs

The investment needs have been estimated on the level of innovation programmes based on inputs from the working groups. Some guiding principles were used to make the investment estimates more balanced and internally consistent.

The scope of the investments includes total investments of the project (CAPEX for the innovative parts and costs of testing, including materials etc.). The scope is as small as possible to deliver the insights required for the aimed for TRL. This means that for use of hydrogen, H<sub>2</sub> production and transport is not in scope, but only the integration of hydrogen in the industrial process is.

For each TRL category, typical investment ranges are defined based on expert judgement from A.SPIRE experts and Navigant's project experience. These ranges are not applied across all innovation in this roadmap, as in some cases there were reasons to deviate (e.g. in the case of digitalisation or smaller modular technologies).

	TRL1-3	TRL4-6	TRL7-8	TRL9
<b>Description</b>	Research and development	Towards a pilot	Demonstration	First of a kind demonstration plant
<b>Range of investments</b>	€2-€4 million per project	€5-€20 million per project	€10-€50 million per project	€40-€200 million per project

For the innovation programme Upgrading secondary resources (A-10.c), we deviated from this approach and used the following data points:

1. The data ranges in the above table
2. Data estimated by Ludo Diels based on previous recycling projects in SPIRE
3. Data obtained in an interview with a A.SPIRE member leading many chemical recycling projects
4. (A brief analysis of 14 recycling projects in CORDIS displayed lower costs, but this approach was considered less representative and thus these data points have not been used below)

Data source	TRL1-3	TRL4-6	TRL7-8	TRL9
1. Default investment range (millions)	€2-4	€5-20	€10-50	€40-200
2. Previous recycling projects SPIRE (millions)	€6-8	€8-10	€10-12	€20-40
3. Chemical recycling (millions)	€3-5	€6-10	€15-20	€50-100

Used costs (millions)	€5	€8	€15	€40
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## E-6 Energy and carbon prices

Consistent energy and carbon prices assumptions are used in the innovation programmes where needed 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	€/tCO <sub>2</sub>

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. This might result in an overestimation. 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 it is more representative for process industry than the lower bands. Many installations will consume more, but as reporting of energy consumption statistics is voluntary for band IG, there are many data gaps. Therefore, this may be an overestimation. 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 it 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/tCO<sub>2</sub> is used, which is in line with the carbon prices of this year (i.e. 2019). Additionally, a carbon price of €150/tCO<sub>2</sub> is used to show the range of possible carbon prices.

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