PROCESSES4PLANET

Strategic Research and Innovation Agenda

Update

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Processes4Planet SRIA Update

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1. Introduction

The process industries are a major contributor to the quality of life of humankind, as they provide materials which are the basis of key elements of the present state of development, from computers and transportation systems to drugs and health care systems, to name just a few. The process industries are also a major source of wealth and income, and hence social stability, of the European Union (EU). Currently, the process industries provide about 8.5 million jobs directly and 20 million indirectly in Europe, and have a turnover of €2 trillion/year, drive innovation, and develop solutions for societal problems. However, processing materials at scale has also significant impacts on the environment and carries inherent risks that need to be managed and reduced to the maximum extent possible. Improving its products and production processes, reducing environmental impacts during the production, use, and eventual end-of-life processing of these products have topped the agenda of the process industries since their beginning. The co-programmed partnership Processes4Planet (hereafter P4Planet) and its predecessor, the Sustainable Process Industry through Resource and Energy Efficiency (SPIRE) public-private partnership, have efficiently driven these innovations forward in the last decade. P4Planet encompasses ten sectors: cement, ceramics, chemicals, engineering, non-ferrous metals, minerals, pulp & paper, refining, steel, and water. Apart from engineering and water, all these sectors belong to the energy-intensive industries (EEI) ecosystem. The current priorities of P4Planet were defined in its Strategic Research and Innovation Agenda (SRIA 2050) that was adopted in 2020. The SRIA 2050 document details a unique collaborative approach to deliver the cross-sectorial innovation that is essential to the transformation of the ten P4Planet sectors. The document formulated three pathways towards an ecologically and economically sustainable European Process Industry in the year 2050:

- Abating emissions for climate neutrality,
- Striving for circularity of materials,
- Enhancing global competitiveness and leadership.

When developing the SRIA 2050 during 2019 and 2020, the first decisions on the European Green Deal (EGD) were agreed upon, and subsequently the EGD has been implemented – and has become more ambitious in its goals – in a broad range of directives, regulations, and acts. For some of the topics, legislation has come into force already. Other topics are under negotiation, and while there is a degree of uncertainty about the details, the proposals of the Commission already sketch the outlines of their future impact. The EGD will have a profound impact on the European process industries and requires well thought-out and fast actions by the industries and the associated research and innovation ecosystem to cope with these changes to its framework operating conditions. The targets set now for 2030 and 2040 are much more ambitious than they were back in 2019-20 when the P4Planet SRIA 2050 was written. For example, much higher targets for the use of renewable energy and reductions in greenhouse gas (GHG) emissions are now envisaged for 2030 and 2040.

Also, other major events have had a significant impact on the current and the future conditions under which the process industries will operate. The COVID-19 pandemic had a deep impact on how we view our supply chains and also on the organisation of work in companies and in the innovation ecosystem. The Russian attack on Ukraine with the resulting embargoes made the dependency of the EU on external supplies of important resources and carriers of energy more visible and caused significant economic problems for the process industries, from which they have yet to recover. Moreover, international competition has sharpened, for example, the Inflation Reduction Act in the US and a broad range of state-supported activities in China. As a consequence, the European process industries are under enormous pressure to meet the climate and circularity targets on the one hand and to stay globally economically viable on the other. The events of the last years have also drastically exposed the risks of not maintaining an industrial base that is able to produce key materials for the needs of society in Europe. Hence the survival and long-term resilience of sustainable process industries in Europe are more important than ever.

Resilience for the European Process Industries implies a greater independence from imports, with as much as possible sourced from within Europe, by Europe. This takes the form of two vectors: energy independence and raw material independence.

Energy independence is coupled to a fundamental parallel change in the main source of energy from fossil fuels to renewables, which has deep implications for process technologies. Combined energy independence and climate neutrality requires an abundance of renewable energy, which predominantly takes the form of electricity. While the process industries will demand and absorb a significant share of the production of carriers of energy from renewable sources, it has only a limited influence on the transition to power generation from renewables and the provision of adequate distribution infrastructures.

For raw material independence, the process industries will have to increasingly use upgraded secondary resources as replacements for imported primary resources, which may create an additional demand for energy from renewable sources. The use of secondary resources will also create economic benefits for the European economy. This vector is one where the process industries will play a key role and is an important aspect of the P4Planet SRIA 2050. Moreover, resilience requires robust supply chains which can react flexibly to changes in availability and prices, as well as to political developments. Steadily increasing energy and material efficiency will also contribute significantly both to reaching our ambitious climate goals and to reducing Europe's dependency on imports.

The developments during the past three years and the future trends that affect the process industries have been carefully and comprehensively analysed by the Foresight Group of A.SPIRE. The results of these analyses were compiled in the Foresight Report which is summarised in Chapter 2 of this document. In addition, a portfolio analysis of the projects funded under the SPIRE and the more recent projects funded under the framework of P4Planet was performed. This analysis also included relevant projects funded by other EU calls. Moreover, inputs from the members of the Permanent Working Groups of ASPIRE[1] were collected and the research and innovation needs for the next five years were discussed intensely with representatives of the different P4Planet sectors. A summary of this analysis can be found at the beginning of Chapter 3.

This combined evaluation led to a sharpened focus in some areas, while the overall strategic research and innovation agenda was found to be still comprehensive and valid. However, the urgency of the goals for 2030 and 2040 requires action to strive for innovations that can be implemented on a short time horizon. Innovation Actions should target operational deployments within a few years of the end of projects. In addition, breakthrough innovations must be addressed to fill the innovation pipeline *en route* to reaching the 2040 and 2050 goals. The International Energy Agency (IEA) concluded that about half of the technologies needed to reach our 2050 ambitions are still in the demonstration or prototype phase[2].

While the pressure to reach the climate goals is currently dominating the needs of the process industries, increasing circularity of materials, which is related to the goal of climate neutrality but also going beyond it, respecting planetary boundaries, and developing more human-centric, resilient process industries are pushing the process industries to innovate while maintaining their competitive global position, generating wealth, employment and well-being for European citizens. The result of the P4Planet SRIA 2050 update is the definition of seven technical priority research and innovation themes for the coming years that are fully coherent with the initial vision of the SRIA 2050.

These priorities are described in more detail in Chapter 3. All the priorities are cross-sectorial and reflect the urgent needs of the process industry as a whole. They are complemented by suggestions on how the transfer of innovations to full industrial use can be accelerated. These are discussed in Chapter 4 "Making it happen".

[1] See Appendix 2
[2] https://www.iea.org/reports/net-zero-by-2050

2. Key elements and impacts of the European regulatory and policy framework

2.1. Climate

In 2018, the EU process industry relied about 80% on fossil energy (including electricity generated from fossil sources) and about 20% on non-fossil energy; almost all fossil energy (oil, gas, coal) used was imported from outside the EU. Thus decarbonisation, as well as resilience, require a drastic reduction in the use of energy from fossil sources which is being tackled through a significant number of European regulations.

Electrification is one of the key pathways to climate-neutrality in the process industry. The EU is putting in place a regulatory framework including the Emissions Trading System (ETS), the Carbon Border Adjustment Mechanism (CBAM), and the Energy Efficiency Directive (EED) which, in combination with the increased availability of renewable electricity for industry fostered by the Renewable Energy Directive (RED III), the Electricity Market Reform, and the Net-Zero Industry Act reinforce electrification of the process industries as a key element of the reduction of the CO_2-emissions in Europe in the years to come. The new 2030 reduction target for ETS emissions is 62% (previously 43%) compared to 2005 emissions. Free emission allowances will be phased out completely by 2034. The hard target for 2030 is 42.5% (previously 32%) of renewables as the source of electric energy, and the agreed ambition is even higher at 45% renewable energy in final energy use. The indicative target for the increase in the share of renewable sources in the total amount of energy sources used for final energy and non-energy purposes in industry is 1.6%/year as an annual average calculated for the periods 2021 to 2025 and 2026 to 2030. CBAM, a carbon tariff on carbon intensive products imported by the EU, will enter into force in its transitional phase as of October 2023, and the payment system will take effect in 2026, with reporting starting in 2023. The CBAM will initially apply to imports of the following goods: cement, iron and steel, aluminium, fertilisers, electricity, and hydrogen. Imports of goods under the CBAM will be subject to the same carbon costs as if they were produced in the EU, therefore averting carbon leakage.

On the supply side, the Electricity Directive and Electricity Regulation and the Wholesale Energy Market Integrity and Transparency (REMIT) Regulation aims to further reduce friction in the electricity market leading to greater transparency for (industrial) consumers in terms of access rights and tariffs, and to improved consumer rights, protections and empowerment. Measures include incentivising demand side response, i.e. flexible operation for example by lowering the minimum bid size and providing more flexibility for (industrial) consumers to share power and storage capacity with other consumers, enabled by an appropriate IT infrastructure provided by the Member States. The initial proposal on the Net-Zero Industry Act aims to accelerate the transition of European industry by more rapid permitting procedures for projects that deliver for the climate transition, and to allow for limited state aid for strategic projects. But it does not include the technologies needed to integrate renewable electricity in the process industries or other technologies essential to decrease GHG emissions in the energy intensive sectors except for Carbon Capture Utilisation and Storage (CCUS). “Sandboxes” can be created to demonstrate technologies where, on a temporary basis, exemptions can be created to enable demonstration of technologies.

Most legislation referred to supports not only the use of renewable electricity as a source of renewable energy for the industry but also of other renewable energy sources such as heat (e.g. thermal solar) and bio-methane. This will also contribute to creating a market for alternative fuels based on renewable electricity and renewable hydrogen. There are two binding targets at national level to ensure that the contribution of renewable fuels of non-biological origin used for final energy and non-energy purposes shall be at least 42% of the hydrogen used for final energy and non-energy purposes in industry by 2030 and at least 60% by 2035. The EU aims at reaching 10 million tons of domestic renewable hydrogen production and 10 million tons of imported renewable hydrogen in line with the REPowerEU Plan. Competitively priced hydrogen will lead to a fast increase in the use of renewable hydrogen as an energy carrier and feedstock in the process industries. The business case for importing renewable feedstock/energy carriers will improve, not only for hydrogen but also, for example, ammonia. Conditions for the creation of large-scale hydrogen networks are being put in place.

However, a recent study by VITO/EnergyVille for A.SPIRE[3] shows that even with high ambitions in terms of renewable energy deployment in Europe, it will not be possible to fully transform industrial production processes towards renewable energy sources since a structural renewable energy shortage is expected to remain in Europe at least until 2030. There will be competition between all sectors for renewable electric power, in particular with the large non-industrial sectors of transportation and heating of buildings. Therefore, it remains crucial that energy efficiency is further increased. Moreover, the generation of electric power from renewables fluctuates, daily, seasonally, and stochastically due to weather conditions. As the electric power grid has hardly any storage capacity, production flexibility is needed to adapt to the availability of green power (demand side management) as well as increased storage of energy in other forms, e.g. hydrogen. Both the flexible use of the production capacity and the storage of energy however increase the pressure on resulting production costs, as both increase capital cost due to the large investments needed and the transformation, e.g. power to hydrogen, comes with inherent losses.

In parallel with the integration of renewable electricity, alternative renewable energy sources (e.g. solar, biomass) and low carbon energy sources (combined with carbon capture or nuclear) need to be considered within the transformation process. Furthermore, import of alternative energy carriers will need to be considered in the transformation process of the EU process industries.

The Communication on Sustainable Carbon Cycles released in December 2021 aimed to develop a long-term vision on how to develop sustainable solutions to increase carbon removal for a climate-neutral EU economy and to support the development of technological and nature-based solutions. This Communication recognises the essential role of carbon for our societies and economies and aims at responsible management of carbon as a resource. Specific aspirational targets[4] are included in the Communication under the so-called “Industrial Sustainable Carbon Challenge”. Major new support actions introduced in this Communication focus on carbon removal and CCUS including the development of a dedicated certification framework.

Further to the “CCUS Fora” organised by DG ENERG in 2021 and 2022 and initially mainly focused on carbon capture and storage (CCS), an Industrial Carbon Management Communication is expected to be published in Q2 2024. The objective of the Commission is to propose an EU strategy to create an industrial carbon management market by 2030 to support efforts in hard-to-abate sectors that need to apply carbon capture and storage, carbon capture and utilisation or industrial carbon removal to become climate neutral. This communication is expected to consider various issues including infrastructures, policy, regulatory, support measure aspects.

2.2. Circularity

Since the development of the P4Planet SRIA 2050 in 2019, the concept of Circular Economy has gained more traction with the launch of the EGD. The goal of Circular Economy is to decouple resource consumption and wealth creation. Currently the level of circularity overall is still marginal at a global rate of 7.2% according to the Circularity Gap Report 2023[5].

The scientific baseline from the International Panel on Climate Change (IPCC) has integrated technology development, including for increased circularity into the context of the EGD. This has led to numerous policy adjustments such as the updated Circular Economy Action plan in 2020 with a greater emphasis on holistic value chain management (strategic value chains) rather than recycling targets. The “Fit for 55” targets and the EU taxonomy criteria offer a financial perspective of increasing competitiveness for circular economy investments. With the disruptions from COVID-19 and

[3] https://vito.be/en/projects/aspire-industrial-electricity-needs-eu-2030

[4] (a) By 2028, any ton of CO_2 captured, transported, used and stored by industries should be reported and accounted by its fossil, biogenic or atmospheric origin.
(b) At least 20% of the carbon used in the chemical and plastic products should be from sustainable non-fossil sources by 2030, in full considera-tion of the EU’s biodiversity and circular economy objectives and of the upcoming policy framework for bio-based, biodegradable and composta-ble plastics.
(c) 5Mt of CO_2 should be annually removed from the atmosphere and permanently stored through frontrunner projects by 2030.

[5] The Circularity Gap Report 2023. Circle Economy, Amsterdam 2023.

the Ukraine war, resilience and strategic autonomy have become strategic priorities for the EU. Safe procurement of resources through smarter resources management and recycling aligns perfectly with Circular Economy.

The Eco-design Regulation includes technical specifications but also transparency for consumers. It embraces end-of-life management (such as extended producer responsibility, collection targets and obligations, targets for recycling efficiencies and levels of recovered materials) and implies data transparency management for recycling purpose as well as objectives to ensure that products placed on the EU market in the future are more reusable, durable, energy efficient and repairable. This indirectly affects the process industries as suppliers of materials to end producers. Specific regulations with ambitious targets are in place for batteries, textiles and electric vehicles, creating new business opportunities and technology needs for the process industries.

Demand (and prices) for recycled materials are expected to increase as recycled material content in products is mandated to increase (in particular for specific products like batteries, construction materials, and packaging etc.). The design of materials and products for recyclability becomes more and more important, for example reducing the content of harmful or difficult to recycle additives or materials. The Single Use Plastics Directive and Packaging (SUPD), the proposal for the Packaging and Packaging Waste Regulation (PPWR) and the proposal for the End-of-Life Vehicles Regulation are also very relevant regulations in this regard. In addition to setting targets for collection of materials and plastic recycling and recycled content for plastics and other materials, they include requirements for the design of associated products and packaging. New technologies and business models will be required for recycling of urban as well as industrial waste streams (for example for solvents or electronic equipment).

The proposed Critical Raw Materials (CRM) Act and accompanying Communication aim to increase resilience and reduce the dependency of the EU on imported materials. It sets clear targets for domestic capacities along the strategic raw material supply chain and to diversify EU supply by 2030, for example at least 50% of the EU's annual consumption for processing must be European sourced, of which at least 15% must come from recycled materials. For the process industries, this creates an incentive to replace CRM in products and production processes where possible, and the opportunity to develop innovative solutions for CRM recovery and (urban) mining of CRMs.

The disposal of waste in landfills will have to be further reduced. In the context of the current revision of the Waste Shipment Directive, exporting waste from the EU, including plastic waste, that is destined for disposal outside the European Free Trade Area (EFTA) is expected to be prohibited. Exports of waste destined for recovery from the EU to non-OECD countries will be banned and from the EU to OECD countries will be subject to the “prior notification and consent procedure”. The Waste from Electrical and Electronic Equipment (WEEE) Directive requires the separate collection and appropriate treatment of WEEE and sets targets for WEEE collection as well as for recovery and recycling. This can also become an important sector for the process industries.

The European Research Area (ERA) industrial technology roadmap for circular technologies in energy-intensive industries, textile and construction ecosystems[6] emphasises the need to take a full lifecycle approach for technology development. In particular, digital technologies and business models play a key role in the transition of all three industrial ecosystems to the circular economy, including in data collection, material tracking and waste management.

2.3. Planetary boundaries

The Zero Pollution Action Plan has, among others, the targets to

- improve air quality to reduce the number of premature deaths caused by air pollution by 55%,
- improve water quality by reducing waste, plastic litter at sea (by 50%) and microplastics released into the environment (by 30%),

[6] European Commission, Directorate-General for Research and Innovation, ERA industrial technology roadmap for circular technologies and business models in the textile, construction and energy-intensive industries, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2777/188014

- reduce by 25% the EU ecosystems where air pollution threatens biodiversity,
- significantly reduce waste generation and reduce by 50% residual municipal waste.

For the process industry this implies a strong pressure to continuously reduce the use of harmful substances both in products and in production processes and to replace them by more benign alternatives. Industry needs to boost its innovative capacity for the development of materials and production and recovery processes that are Safe and Sustainable by Design (SSbD) and increase investment in their production. SSbD considers safety in materials, worker exposure and release during production, and use phase exposure as well as after the product's useful lifetime. Supportive roadmaps for SSbD are under construction for different sectors including packaging, textiles, automotive, energy materials, electronics, construction, and fragrances.

The 2022 Industrial Emissions Directive (IED) proposal that regulates pollution from certain industrial activities has an increased focus on energy, water and material resource efficiency and reuse, as well as promoting the use of safer and less toxic, or non-toxic chemicals in industrial processes. We must ensure that depollution and decarbonisation techniques occur together, where possible, to achieve the best health and environmental outcomes and harness technological and investment synergies.

Microplastics have become a significant concern due to their ubiquitous proliferation and the unknown impact on human health and on nature. Currently there are no specific instruments in place, but in view of the risk to animal and human health, measures can be expected to be forthcoming in the next few years.

2.4. Industry 5.0

Industry 5.0 is a broad strategic vision fostered by the European Commission. The framing is that industry becomes a resilient provider of prosperity by making production respect the boundaries of our planet and placing the wellbeing of the workforce and customers at the centre of the production process. The central goal of Industry 5.0 is a human-centric (placing societal demands and human interests in the foreground), sustainable (respecting planetary boundaries) and resilient industry (in all its components, including production processes, supply chains and procurement of raw materials). It aims to empower the workforce to select, use and develop processes and procedures, unfolding the innovative potential in the workplace, but also to empower investors and consumers to obtain reliable information about products and production processes, especially with respect to sustainability. To ensure consumers receive reliable, comparable and verifiable environmental information on products, claims must be substantiated with scientific evidence that is widely recognised, identifying the relevant environmental impacts and any trade-offs between them. Claims or labels that use aggregate scoring of a product's overall environmental impact on, for example, biodiversity, climate, water consumption, or soil, etc. will not be permitted, unless specified in EU rules. Environmental labels must be transparent, verified by a third party, and regularly reviewed.

The EGD already contains a extensive set of regulations focusing on transparency for the wider impact of industrial companies on society. The goal of these regulations is to give societal groups such as consumers, investors and the labour force a clearer insight into the score of a company on the three key aspects mentioned below. Rather than regulating directly, this type of regulation empowers societal stakeholders to drive change. Three key transparency elements are:

- Benchmarking of companies with respect to their footprint. This benefits not only financial stakeholders (from banks and investors to shareholders) but also enables potential employees to take the footprint of a company into account when deciding whether to work for a company,
- Transparency for consumers on the sustainability of products will need to be fact-based,
- Resilience, for example in terms of reliance on critical raw materials and critical supply chains will become an integral part of the sustainability assessment.

The Non-Financial Reporting Directive (NFRD) is currently being revised (renamed as the Corporate Sustainability Reporting Directive (CSRD)), with the aim of delivering a comprehensive corporate reporting framework with qualitative and quantitative information to facilitate the assessment of companies' sustainability impacts and risks. The proposal aims to:

- Extend the scope to all large companies and all companies listed on regulated markets (except listed micro-enterprises),
- Require the audit (assurance) of reported information,
- Introduce more detailed reporting requirements, and a requirement to report according to mandatory EU sustainability reporting standards,
- Require companies to digitally 'tag' the reported information, so it is machine readable and feeds into the European single access point envisaged in the Capital Markets Union Action Plan.

The Industry 5.0 vision will lead to new value propositions meeting sustainability related consumer needs, broader stakeholder and citizen engagement, and social acceptance. Important elements for the implementation of the concept are responsible management of resources, empowerment of the workforce, co-creation and co-design of technological solutions, and a safe and inclusive work environment protecting physical and mental health of the workforce.

3. R&I Priority Themes

3.1. Results of the portfolio analysis and of the discussions with the P4Planet sectors

In our project portfolio analysis, a total of 191 projects were included, of which 130 projects were funded under Horizon 2020 including most projects that were funded under the framework of the SPIRE public-private partnership. A further 27 projects were funded through Horizon Europe under P4Planet calls (which were still in the initial phase), and 34 other relevant projects funded under other schemes, including projects supported by the Innovation Fund, were included.

From the analysis of these projects, it can be concluded that there has been a good coverage of the topics related to CO_2 capture and utilisation, energy efficiency (including heat reuse), integrating renewable energy, circularity, and digitalisation. The total number of projects in the area of circularity is high, but among these were many projects that reached only middle Technology Readiness Levels (TRLs 5-6). Among the projects on industrial and industrial-urban symbiosis, there were many that targeted software tools and analytic results on the potential for symbiosis. On the other hand, electrification and the use of hydrogen as a carrier of energy and/ or feedstock was covered only by few projects.

Of the 43 projects funded under P4Planet calls in the Horizon Europe Work Programme 2021-23, a relatively large number of projects address the areas of circularity of materials (27) and digitalisation (18 - mostly as an enabling technology). In addition, due to the relatively low number of projects so far, many areas are covered but by only a few projects. The projects often were related to several Innovation Areas of the SRIA 2050.

Regarding the additional activities of the industry which had a total financial volume of € 662 million in 2021/2022, the focus was in the areas of integration of renewable energy sources (17 activities), energy and resource efficiency (14 activities), and circularity of materials (11 activities). Eight additional activities were related to CO_2 and CO utilisation.

Over the past years, enterprises in the process industries have all developed strategies and projects for decarbonisation and increased circularity that reflect the ambitious goals of the EU. Summarising these strategies, the following elements stand out:

- Fundamental changes of process technologies through electrification and using renewable hydrogen.
- Shift of energy inputs from fossil sources to renewable electricity and other carriers of energy from renewable sources, including, among others, hydrogen, ammonia, and biogas.
- Improved energy and material efficiency and intermediate steps to reduce emissions without complete substitution of fossil carriers of energy.
- Carbon capture and storage / utilisation.
- Use of renewable feedstock.
- Use of production waste and end-of-life waste to generate feedstock for new products.

The process industries are currently implementing an impressive number of large projects that will lead to demonstration plants at production scale based on new technologies. For example, CCUS projects (some of which are financed by the Innovation Fund), new technologies for the production of steel (with total investment of over €4 billion in Germany alone), electric crackers, and plastics recycling plants (including a planned investment of €1 billion for a plant for polyester recycling by Eastman in France). This shows unprecedented broad and large-scale investments in the transformation of the industrial base in Europe related to the climate and circularity goals.

In view of the current research and innovation strategies of the process industries, and the forward-looking analysis of future trends and regulations, P4Planet has defined seven overarching priority themes for the next years which are all aligned the original SRIA 2050. They are:

- **Electrification of the process industries**
- **Alternative carriers of energy and their integration**
- **Accelerated improvement of energy and material efficiency**
- **Carbon capture and utilisation**
- **Materials and production processes that are safe and sustainable by design**
- **Circular economy**
- **Digitalisation, and human-centric industry**

These priority themes are discussed in detail below.

3.2. Electrification of the process industries

Across all sectors, most production processes in the process industries require the input of energy to perform transformations and separations of materials. The replacement of the input of energy from fossil sources by electric power from renewable sources will be a major contributor to reaching the 2030 and 2040 climate goals for all process industries, and the key contributor for many of them. This can take place by direct energy input into processes or via electrochemical processes to convert electric power to intermediate carriers of energy, such as hydrogen, and their use. Electrification technologies will need to be available faster and at a larger scale than foreseen in the original SRIA 2050 roadmap.

However, electric power generation from renewables will be limited in the coming decade, and currently the price of electricity is considerably higher than the price of fossil carriers of energy. Decarbonisation of the process industries requires a rapid growth in the generation of power from renewables, large investments in transmission and distribution systems, and prices which keep the process industries in Europe competitive. As the share of electric power generated via renewables remains only a fraction of the total power mix, and there is competition for supply with other sectors, the efficient use of the electric power input is imperative.

Currently many sites in the process industries are using heat as the main input of energy into their processes. Heat is provided by steam networks at different pressure levels that also take up surplus heat from exothermal processes.

Steam and electricity are generated by combined heat and power plants (CHP, usually gas fired) which is the energetically most efficient way of generating electric power from fossil sources. When electrification of many processes is implemented, the energy infrastructure of the sites has to be re-thought and modified.

Generally, all processes have to be re-thought in the process of electrification, beyond generating heat from electric power, for example by using electrochemical processes, mechanical energy inputs in separation processes, or by activation of reactions through other forms of energy than heat. Substantial activities in research, development, demonstration and deployment of electrified process operations are needed in the coming years.

With the transition of the power generation from fossil to renewable sources, large variations in the amount of renewable electricity and of the price of electric power will occur. In the medium term, excess energy cannot be captured by batteries or other forms of direct storage. Therefore, it is key to increase the flexibility of production plants to be able to follow the power generation pattern and to operate at different load levels in a dynamic fashion. This requires process redesign and advanced automation, including the use of model-based optimisation in real time.

Strategic research innovation themes

Heat generation and heat upgrade

- Heat pumps: Further improvements of performance over a wide range of conditions, large scale high temperature heat pumps, integration into existing and redesigned processes, more flexibility in operational parameters.
- Electrified production of high-pressure steam.
- Electric heating of high-temperature processes > 500ºC: hybrid furnaces, full electrification, heat storage and re-use, drying at high temperatures.
- Design and control strategies of new large-scale energy systems based on heat pumps.

Electrification of conversion processes

- Electric crackers.
- Electrochemical and electro-catalytical conversions.
- Direct electric heat input (e.g. microwaves, plasma, etc.).
- Heat to electric power conversion.

Electrically driven separation technologies

- Electric heating concepts in separations.
- Replacement of heat by mechanical power input (e.g. HiGee distillation, membrane technology, vapour recompression).
- Electrochemical separations.
- Drying by electricity induced forces.

Production processes with significantly higher flexibility and a high efficiency over a broad range of conditions

- Improved process and equipment design that enable operation over a large range of loads without increased degradation of the equipment.
- Design and demonstration of large-scale integrated systems with multiple streams of materials and carriers of energy.
- Advanced control and model-based optimisation.

This priority theme is directed towards the achievement of KPI 1 of the P4Planet Partnership (see table in Appendix 1).

3.3. Alternative carriers of energy and their integration

As well as the direct input of electric power, other sustainable energy carriers (hydrogen, ammonia, methanol, syngas, and biogas etc.) will play a significant role in the decarbonisation of the process industries. Highly efficient technologies for their production and use in production processes must be brought to high TRLs quickly. The selection of options will depend on the specific conditions of the different sectors and applications. In addition to advancing high TRL technologies, the development of other alternatives for energy input, such as heat from solar concentrators, should be pushed forward. Energy efficiency is key to achieve decarbonisation for all industry sectors. This also means that for all alternative renewable energy sources and fuels, it is crucial to use them as directly as possible and to avoid conversion, and thus conversion losses, to secondary energy carriers or fuels when this is not needed.

As already stated in the SRIA 2050, P4Planet has set the target that, through research and innovation projects that reach TRL 7 in 2030, a 100% CO_{2eq} emission reduction potential can be demonstrated by that date. As well as electrification and improvements in energy efficiency, the production and use of hydrogen will play a key role. The technologies in this area are being advanced by both the Clean Hydrogen Partnership and P4Planet in a coordinated approach. There are large investments planned on the European and national level supported by the IPCEIs (Important Projects of Common European Interest) Hy2Tech, Hy2Use and Hy2Infra. The Clean Hydrogen Partnership focuses on the production of renewable hydrogen, its transport and distribution, and applications in transportation and clean heat and power, while P4Planet drives the application of hydrogen as a carrier of energy and as a feedstock in the process industries. In addition to hydrogen, other carriers of energy should not be neglected as they offer specific advantages, such as higher density and thus smaller cost of transportation, and less demanding safety issues. Bio-based resources will also play an important role in providing energy inputs to the process industries, both directly and via the production of biogas.

An overarching theme in this area is the need for the integration of different carriers of energy (electricity, hydrogen, steam, ammonia, methanol, and others), and of storage systems at different scales including at plants, production sites, industrial parks, in regions, Europe-wide and beyond. Integrated design and operation of these highly complex systems are needed to cope with the fluctuations of the energy inputs and to achieve overall energy and cost efficiency. This requires full digitalisation, the application of model-based technologies, good operator advisory systems and training of the operating staff to cope with continuous fluctuations and unexpected events.

Strategic research and innovation themes

Cost and energy efficient integration of hydrogen into the plants of the process industries: integrated system-wide solutions, flexibility, demand-side response, and digitally supported system management, including

- High temperature heat, furnaces, multi-fuel process equipment.
- Hydrogen as a reducing agent.
- Use of hydrogen or other carriers of energy to buffer fluctuations of electric power.
- Hydrogen replacing fossil feedstock.
- Integration of heat and oxygen from hydrogen electrolysers.

Production and integration of other carriers of energy (ammonia, methanol, biogas etc.)

- Efficient production technologies.
- Technologies for the use of ammonia and biomethane as fuels.
- Conversion coupled to efficient power generation (e.g. offshore).
- System solutions on different scales: plants, sites, industrial parks, regions, Europe and beyond.

Direct use of solar and geothermal heat

- Concentrators to generate high temperature heat input and their integration into production plants, buffering of diurnal variations.

- Geothermal heat input into production processes.

Advanced heat re-use including storage systems for adaptability and flexibility

This priority theme is directed towards the achievement of KPI 1 of the P4Planet Partnership (see table in Appendix 1).

3.4. Accelerated improvement of energy and material efficiency

This theme concerns the improvement of the energy and material efficiency within the limits of the production systems (including sector coupling). The processing of post-production waste is dealt with in the section on circularity.

While the introduction of other carriers of energy than those from fossil origin will be required for large steps forward in the reduction of CO_2 footprints, complementing this, the energy efficiency of production processes in the process industries must be improved further. As well as the implementation of technical improvements and breakthrough technologies on the scale of equipment and process design, better operator support, automation and optimisation, and coordinated production can contribute significantly here. The use of energy that is generated as a by-product, within plants, between different plants (Industrial Symbiosis), and by the urban and regional environment (Industrial-urban Symbiosis) must be intensified further. A contribution to the reduction of energy inputs could also be provided by the wider use of biotechnology/ biologically inspired transformations which do not require high temperature levels or additional chemicals. Here a key topic is the increase in the efficiency of water removal for products generated at a high dilution.

Projects in this domain should predominantly aim at reaching high TRLs and long-term demonstrations at scale in real-world environments.

Equally important is the increase of material efficiency in the production sector to reduce the amount of waste that goes to incineration or landfill and to make the best possible use of the substances which are contained in by-product streams and auxiliary substances, in particular solvents and water. This also indirectly contributes to an increased energy efficiency and a better life-cycle assessment (LCA), as the energy and material inputs for the production of these substances are largely reduced. This requires industrial symbiosis between different plants and sectors and industrial-urban symbiosis regarding the treatment of wastewater.

An important contributor to material efficiency is the development of new catalysts and of efficient processes around these. Catalysts are needed that have a higher specificity and activity, are easier to recycle, use fewer precious materials, and are more tolerant to impurities. Connected to the issue of critical raw materials, the recovery of catalysts that contain noble metals is of high strategic importance.

Further progress in the domain of material efficiency requires both research-oriented projects as well as projects that target high TRLs and long-term demonstrations in real world environments.

Strategic research and innovation themes

In-process energy efficiency improvements (aiming at high TRL and long-term demonstrations at scale)

- Process intensification and integration to reduce losses of energy and material.
- Recovering the energy content of side-streams, e.g. wastewater.
- Innovative de-watering and drying technologies for energy saving.
- Reduction of steam venting and re-use of condensate.

Industrial and industrial-urban symbiosis to increase energy and material efficiency

- Novel energy and material integration schemes as required due to the introduction of electricity, hydrogen and other carriers of energy, and their stable and efficient operation.

- Demonstration of industrial and industrial-urban symbiosis of sustainable processes.
- Innovative solutions for the coupled efficient operation of plants and joint infrastructures under fluctuating conditions, considering the limits on information sharing.

Reduction of the intake of fresh water by the process industries

Extraction of valuable substances in small concentrations, in particular from wastewater, to the extent justified by an integrated LCA and cost analysis as well as strategic and political considerations

- Energy and cost-effective technologies for water treatment (including the isolation of components of concern).

Next generation catalysis

- Alternative catalysts that use non-CRM metals.
- Innovative catalyst recovery, purification and re-activation processes.
- Joint development of catalysts and processing systems for alternative energy inputs.
- Alternative catalyst configurations to improve mass transfer, advanced coatings, single atom layer catalysts.
- Integration of bio-based catalysis in cooperation with the Circular Bio-based Europe Joint Undertaking (CBE JU).

This priority theme is directed towards the achievement of KPIs 1, 3, 4 and 5 of the P4Planet Partnership (see table in Appendix 1).

3.5. CO_2 capture and utilisation

While the integration of renewable energy carriers and the advances in energy efficiency will decrease energy related emissions, unavoidable process CO_2 and CO streams (not related to generation of heat and electric power, such as CO_2 resulting from the production of cement) will remain in many P4Planet sectors. Besides reducing the generation of CO_2 in the industrial production processes, Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) will be essential for several P4Planet sectors, such as cement, to reach the EU climate targets. The first permits for carbon storage have been provided by the UK, Norway, and recently Denmark and several large-scale projects on CCS and CCU in different sectors have been launched with support from the Innovation Fund.

As carbon is needed for the production of many materials and chemicals, CO_2 is one of the non-fossil alternative carbon feedstocks, along with bio-based resources and carbon containing waste such as plastic waste, for the P4Planet sectors. These sectors are therefore aiming to improve further the efficiency, cost and ecological footprint of processes for the conversion of their captured CO_2 and CO streams into products (concrete, building materials, polymers, chemicals, fuels) to decrease their CO_2 emissions and increase carbon circularity. In addition, alternatives to the already established processes should be explored further including biotechnological routes in collaboration with the CBE JU.

Further research and innovation is needed to optimise carbon capture, conversion into sustainable products and carbon storage in an integrated energy efficient fashion. It is expected that an optimum in efficiency and CO_2 emission reduction can be obtained through a combination of CCS and CCU that will shift over time with the increase in the share of power from renewables.

The efficiency of carbon capture and purification in terms of energy input as well as ecological footprint and cost must be improved further. Along with the improvement of existing technologies, alternative routes such as electrochemical CO_2 separation technologies should be developed. The development of technologies for low concentrated point sources (2 - 8%) is also needed. In the long term when electric power from renewable sources is abundantly available, Direct Air Capture technologies can also contribute to CO_2 removal from the atmosphere, however major challenges related to energy efficiency need to be addressed for their implementation.

As CCU requires industrial symbiosis, future plans for the development and implementation of CCU technologies will have to consider the expected changes in industrial CO_2 sources resulting from the transformation of some sectors, such as iron and steel. The deployment of CCU entails large investments which will only be made if the boundary conditions are clear and stable. The future of CCU and CCS is highly dependent on the political and regulatory framework conditions as well as on infrastructure development which currently are uncertain and heterogeneous across countries despite the EU CCS Directive.

Strategic research and innovation themes

Improved efficiency of CO_2 (and CO) capture and purification at reduced cost

- Improved handling of sulfur and nitrogen compounds as well as other impurities from industrial sources.
- Improved utilities management including heat exchange and electrification.
- Improvement of the kinetics of adsorption and desorption.
- Design and production of advanced sorbent materials including surface modified sorbent materials for optimal CO_2 capture performance from different sources (including low concentration streams).
- Development of electrochemical CO_2 extraction separation technologies.

Advanced technologies for CO_2 utilisation – CO_2-to-products

- Improvement of catalytic conversion processes (improved tolerance to impurities, lower concentration in feed, higher yields) and new intensified processes.
- Development and improvement of electrochemical conversion processes for a wider range of target molecules including base chemicals.
- Development and improvement of biotechnological and bio-electrochemical conversion processes for a wider range of target molecules.
- Development of a broader range of mineralisation routes from various waste sources.

The targeted products should be prioritised based on a sustainability assessment considering their full life cycle.

This priority theme is directed towards the achievement of KPI 2 of the P4Planet Partnership (see table in Appendix 1).

3.6. Production processes and products that are safe and sustainable by design – Towards Zero pollution

Along the complete value chain, from the production of materials to end of life of products, it is necessary to guarantee safety and sustainability for humans and the environment. In addition, the dependency of Europe on other regions of the world, especially for strategic raw materials, must be reduced. The role of materials in the economy can be classified into two main categories that need different design, management and processing strategies: service materials that are integrated into products that provide long lasting services, and consumption materials that are designed for short lifespans. For the first group of materials, circular strategies and products and materials designed for a closed loop system are needed, while materials in the second category need to be designed so they can be reintegrated into the biosphere without harm.

The development of safe and sustainable materials and the development of the related production processes are tightly coupled. In the design of materials, both their performance, the options to produce them, and the consequences for a circular economy where these substances are reprocessed must be considered from the start. The use of substances with negative impacts on health and the environment in products and in production processes must be avoided, but also negative impacts that may materialise years or decades later from these substances in recycling and reprocessing systems. Potentially disturbing components for this reprocessing have to be avoided to the greatest extent possible. This includes options for their separation from the materials in final applications as well as their recognition in separation processes. This holds across almost all sectors, from steel to chemicals and pulp and paper.

The co-design of materials between the suppliers and the companies that process them into products is a common characteristic for the development of high-performance materials in all sectors of the process industries. This collaboration will have to be extended to include companies that participate in the collection, classification, dismantling and separation of the waste streams as well as those that re-process the waste into feedstock for the process industries. In the design and production of future materials, the accumulation of additives and pollutants over several recycling cycles has to be considered. As the process industries are mostly not selling their products to the end-users, this requires an even deeper collaboration than at present along the whole value chain.

In order to include the environmental impact of the production processes early on, digital models of both the materials and their properties and of the associated production processes are required and must be connected to enable appropriate exploration of the design space.

Improved technologies are needed to remove potentially harmful components from all streams that leave the production processes. New challenges arise here as side streams will no longer be used as fuels, so these need to be separated and converted into useful streams where needed. The use of harmful solvents, but also of other auxiliary materials, must be further reduced. Continuous improvements are needed regarding worker exposure and release during production, use phase exposure as well as handling, separation, and recycling after the useful product lifetime. Research and innovation are needed for the substitution of, for example, Per- and Polyfluorinated Substances (PFAS) and their associated processes. The issue of microplastics also requires high attention in the coming years.

Strategic research and innovation themes

Sustainable production processes and products avoiding hazardous substances and lowering pollutant emissions fit for the SSbD framework

- Strategic substitution of materials containing hazardous substances and/ or substances of very high concern (SVHC).
- Avoidance of the proliferation of microplastics by process and materials design.
- Design and production of materials for next generation circularity: consumption materials designed for re-integration into bio- circular nutrient flows and service materials designed for re-integration into the techno-circular flow.
- Industrial processes with drastically reduced emissions into the environment.

Technologies for the recovery of substances from product streams and side-streams

- The selection should be according to the impact at large and a preliminary comparative LCA.

Prototypical approaches and tools for the co-design of materials, production processes, and recycling value chains to generate new feedstock

- Methodologies and software tools to support design processes by integrated simulation of material properties, production processes, and recycling value chains (digital twins).
- Must provide transferable methodologies and examples that are shared broadly, within and between sectors.

This priority theme is directed towards the achievement of KPI 4 of the P4Planet Partnership (see table in Appendix 1).

3.7. Circular economy

The transformation to a functioning circular economy will depend on favourable conditions where new business models that are decoupled from resource consumption have a competitive advantage over their linear competitors. The challenges of the circularity transformation are directly linked to the amounts of materials concerned as well as the value and complexity of those materials. The P4Planet community cannot deal with these challenges alone, but needs to develop the enabling technologies that will make such an economic transformation technically feasible in cooperation with the waste collection and processing sector. Circularity is strongly linked to resilience. All technologies that lead to the circularity or upcycling of materials will increase the resilience of European industry and the economy.

Materials recycling needs can be categorised as post-consumer flows (from products that have reached the end of their useful lifetime) and post-production flows, where the material was not processed up to the final form. While the last category usually consists of homogenous streams of known composition, the first category is characterised by large quantities of highly diverse materials of often unknown composition that are tightly integrated into the products.

Generally, recycling should preserve as much as possible of the value, structure, and energy content of the materials. The preservation of components with sophisticated structures and their use as feedstock is only possible after a significant effort in dismantling, classification, sorting and separation. Technologies for these processing steps need to be developed in close cooperation between the process industries and the waste sector. End-of-life products are generated and distributed over the whole of Europe and the different components and materials need specialised processing to preserve as much as possible the value of the materials and to improve the LCA of their re-processing. Therefore , advanced materials recycling necessitates the creation of large-scale value chains with broad geographical coverage on the input side, but few specialised processing facilities, preferably close to the production sites for new materials.

In some sectors, processes for the collection, separation and (re)supply of materials back into production processes are already well established, for example in the steel and metals industry. In other sectors, especially in the textiles and plastics sector, circular economy faces the problem of a large diversity of substances that are mixed with others (e.g. carbon fibres, flame retardants, colours etc.) and a large diversity of matrix materials. The efficiency of the circular value chains depends crucially on the co-development of collection, sorting and pretreatment technologies in conjunction with design for recycling and upcycling technologies (see section 3.6). Also in the metals sector, the accumulation of other elements over multiple recycling loops has to be accounted for. The inputs from the end-of-life products will always vary in composition, as removing all impurities requires huge efforts and leads to losses of valuable materials. Therefore, robust upcycling technologies that can tolerate varying feedstock, mixtures of materials and varying additives and impurities must be developed in all sectors. In addition, the accumulation of materials of concern must be avoided.

For the next few years, the focus should be on the most impactful waste streams and projects should aim at demonstrators at near production scale. These may also include new business or cooperation models and tools. In the longer term, technologies for the efficient utilisation of a large number of specific waste streams will have to be developed. The implementation of circular value chains will be supported by digital product passports; however it must be kept in mind that for most of the materials which are processed within the next 10 years, this information will not be available, and that information alone does not lead to a separation of the waste. Separation and upcycling of waste streams is also a key contribution to securing the supply of critical raw materials. This will lead to “urban mining” as a new field of activity for the process industries. In particular, WEEE is a very important stream that creates new opportunities for the process industries. The use of bio-based feedstock should be considered as an option, wherever the LCA is positive and sufficient amounts of feedstock are available.

Europe will face an increasing challenge regarding the availability of water for industrial use. Using water of different purity levels and purified wastewater will be required. The composition of process and wastewater varies greatly between different industries and plants. Moving towards a circular economy may cause increased concentrations of contaminants in process water and wastewater, due to accumulation, thus requiring new technologies for adequate treatment, reuse, and recycling of water. A special challenge is to significantly reduce the salinisation of circulated process water and thus surface waters into which cleaned wastewater is discharged. Industry needs an enlarged toolbox of energy and cost-efficient technologies to reduce the water footprint and progress towards circularity of water considering the zero-pollution objective.

As the environmental benefits of the circularity transition are multiple and not primarily carbon emission centric, a holistic impact analysis that includes all factors from CO_2 and pollutant emissions to the resilience and independence of Europe as a strategic goal is necessary. Harmonised LCA calculation methodologies across sectors are needed to guide decision making on circular strategies on material choice and end of life practices.

The transformation towards a Circular Economy presents in equal parts technological as well as economic and regulatory challenges and needs a well-coordinated innovation and intervention agenda across sectors and value chains. A critical aspect here concerns when materials are considered as waste and when they are dealt with under the regulations of feedstock for the process industries.

Strategic research and innovation themes

Robust and flexible technologies for

- Processing of end-of-life materials to become feedstock for the process industries.
- Integrating feedstock from recycling into the production processes of high-quality materials.

Integrated development of technologies and business models for the upcycling of end-of-use and production waste with partners from the waste sector, including

- Technologies for the use of residues and by-products generated during the manufacturing processes.
- Dismantling, sorting, and separation of waste streams.
- Technologies to preserve as much as possible of the value of the materials, guided by a comparative LCA.
- Use of digital technologies to facilitate sorting and separation and to track the inputs and the outcomes of the different stages and to adapt the subsequent steps.
- Strategies to maintain the quality of recycled materials over multiple loops.

Activities should be prioritised according to the importance of the streams and the level of maturity of the technologies so that significant impacts are reached within the next decade and lead to demonstrators at relevant scale that operate under real conditions posed by the delivering and receiving systems.

Recovery of valuable materials, especially Critical Raw Materials, from waste streams

- Priority on WEEE.
- Urban mining, investigation of using landfills as resources.

Circularity of water (supporting industrial and industrial-urban symbiosis)

- Technologies for the removal of substances of concern and of other hazardous substances from water that is used in processes or released to the environment.
- Extraction of valuable substances from wastewater, when the LCA is positive.
- Reduction of the energy input into water treatment.

Analytical tools

- Tools for environmental footprint assessment in line with planetary boundaries and sustainability principles and the strategic goals of resilience and independence of Europe.
- Tools for the prioritisation and choice of technologies for the use of waste as novel feedstock.
- Methodologies to assess the quality of material at end of life, e.g. the presence and risk of certain substances of concern, the material compositions in products/ product groups/ material mixes (e.g., % of recycled content), and material degradation assessment methodologies.

A critical aspect for projects in this area is the long-term support and maintenance of the tools.

This priority theme is directed towards the achievement of KPIs 3, 4, 5, 6 of the P4Planet Partnership (see table in Appendix 1).

3.8. Digitalisation and human-centric industry

Digitalisation

The digitalisation of the process industries is a continuous process that covers the whole material processing lifecycle – starting from material design, through plant operations, supply chain management, customer interactions, and ending up with recycling the material. In the process industries, digitalisation concerns digitally supported materials design, digitally supported process development and engineering, digitally supported plant operation, automation, intelligent material and equipment monitoring, and integrated supply chain management. Digitalisation has been pushed forward by the Industry 4.0 initiative, but the progress especially in brown-field plants has not been very fast. In modern automated plants, there is an abundance of data, but this comes with two challenges. First, most large- scale process plants are equipped with several diverse IT solutions with heterogeneous data sources, data storage systems and data formats. While the transformation of data formats is simple, how to convey context (e.g. what is the position and the calibration of a sensor the readings of which are stored) has not yet been resolved in a standardised manner. Thus, the use of information from these heterogeneous systems involves a significant engineering and maintenance effort. Second, abundance of data does not mean abundance of information. Often the part of the data that is relevant and useful for process monitoring, understanding, and modelling is relatively small, and the selection and use of this data requires the case-by-case intervention of engineers.

Digitalisation will continue to provide significant ecological, economic, and social benefits, but it requires also significant investments especially in the connectivity of legacy systems, semantic labelling of data, cyber-security, training of the workforce and tailoring or development of software which is often not considered to be part of the core activities of industry. The fast-developing IT and software technology, in particular artificial intelligence (AI) provides new opportunities that will have a significant benefit for the process industry when wisely adopted.

All research and innovation priorities discussed in the previous sections of this chapter require the extensive use of digital technologies for design, operation, monitoring, and supply chain management. As described above, electrification, the introduction of new carriers of energy, increased energy and material efficiency by industrial and industrial-urban symbiosis will lead to partly or entirely new production systems that have to operate in a flexible manner while maintaining the highest possible efficiency. Digital tools for their design and operation are indispensable. Demand-side management must be based on dynamic models at different levels of granularity and employ optimisation technology in a real-time environment. Large-scale systemic solutions for the recycling of end-of-use streams of material require coordination of the different steps between different operators and sectors, hence sophisticated digital tools. The design of safe and sustainable materials connected to the design of the production facilities needs the support of digital twins of materials and production plants. The same holds for the LCA of large-scale recycling solutions.

A specific challenge is highlighted both by the demography of many European countries and the need for competitiveness: the transition to partly autonomous operations of plants in the processing industries. Working night shifts does not contribute to the attractiveness of the industry for the workforce. Autonomous plants are transforming human work in industry, taking the form of hybrid work, e.g. working with robotics and AI supporting decision making. The goal is to free humans from dirty, dull, dangerous, dear, and difficult work (5Ds) and empower humans with more meaningful and attractive tasks. All these objectives require development in sensing solutions, human-machine and machine-machine communication, integration of robotics, drones or immersive technologies (AR/VR) and sophisticated algorithmic solutions. The interaction between humans and the plants needs to be designed in a human-centric manner while guaranteeing the safety of the environment, the population around the plants and the plants themselves. Cyber-security is a central aspect when moving forward with digitalisation and automation.

Strategic research and innovation themes

Digitalisation is a core element of almost all innovations that were described in the previous sections. There is a huge need for digital, data, model and optimisation-based solutions to realise the flexible efficient production systems of the future with a minimum CO_2 footprint. Similarly digital tools for process and material design are indispensable and must be further developed and integrated. Specific digitalisation-related topics of a *transversal nature* are:

Operator support and human-machine interaction in the process industries

- Improve the way operators interact with automation and monitoring systems, make the workplace attractive for the operators and enable them to use their capabilities in the best way to improve the efficiency and safety level of the plants.
- Support operators in handling the increased variability and flexibility of the next generation of processes by providing relevant condensed supportive information on the safety, economics and sustainability of the current operation and possible improvements.
- Improved condition monitoring and fault detection.

Towards autonomous plant operations

- Technologies for autonomous operation in real industrial plants including aspects of cyber security.

Integration of heterogenous digital systems in design and operations (in cooperation with the process IT sector)

- Integrated data spaces with semantic annotations.
- Standardised interfaces to connect IT/OT IT systems and real-time systems from different suppliers.

Digitalisation supports the achievement of all KPIs of the P4Planet Partnership (see table in Appendix 1).

Human-centric process industries

In the introductory section, the vision of Industry 5.0 with its pillars of resilience, sustainability and human-centric industry was described. Sustainability and resilience were the focus of the preceding sections of this chapter, here we focus on the human-centric aspect. In this respect, Industry 5.0 is understood as a combination of organisational principles and technologies to design and manage operations and supply chains for the people/society, with the users, customers and relevant stakeholders as active participants in the design and development of technological innovations. It aims to empower employees for selecting, using and deploying the innovative potential of new technologies in the workplace. Human-centric industry includes the protection of the physical and the mental health of the workforce as discussed in the section on safe and sustainable materials and production processes.

Human-centricity is strongly connected to digitalisation as the usability of digital systems by humans determines their acceptance by and the productivity of the users. Workplaces and operational tasks should be analysed to garner the potential of digital tools to increase productivity and safety of operations, to foster human-machine collaboration and human augmentation, and to improve occupational well-being. Digital tools can also be used to collect input and feedback from employees at different levels of the organisation and across sites or even along value chains.

A core element of the sustainability and resilience of the process industries is their motivated and skilled workforce. With the transformations described in the previous chapters being implemented at a fast pace, upskilling of employees will be required so that they can handle the emerging novel, highly dynamic and interconnected production systems of the future.

Strategic research and innovation themes

The Industry 5.0 concept needs to be operationalised for the process industries from the human-centricity perspective, analysing the impact on resilience, sustainability and technological innovation processes. This requires the development of a Process Industry 5.0 framework for engaging stakeholders, to raise awareness, to increase social acceptance, and to gather and exchange good practices.

This involves:

- Investigation of the state of the art qualitative and quantitative tools for measuring progress towards Industry 5.0 in its three dimensions of resilience, sustainability and human centricity and how they are operationalised for the energy intensive industries.
- Stocktaking of good practices. Overview of the state of the art and preconditions for adding the Industry 5.0 perspective to Industry 4.0 related innovations and implementations.
- Measuring the impact of non-technological aspects (skills demands, competitiveness, sustainability, social acceptance, process of implementation of new solutions) in relation to human-centricity and its relevance for sustainability and resilience.
- An evidence-based long-term management of the European Industry workforce and skills needs, based on the results of the Skills Alliance for Industrial Symbiosis. As a result of this analysis, educational materials, courses and programmes should be developed to improve the skill level of the workforce for the challenges of the transition to climate-neutral process industries.
- Benchmarking Industry 5.0 implementation advantages to organisations to date: competitiveness, reputation, attractiveness for talent, attractiveness for investment, resilience, sustainability.

Human-centric industry is a new concept that arose after the approval of the P4Planet SRIA. The activities contribute to reaching KPI 11 of the P4Planet Partnership (see table in Appendix 1).

4. Making It Happen: Accelerating the progress to breakthrough innovations and deployments (First of a Kind Plants)

4.1. Hubs4Circularity

Hubs for Circularity (H4C) in the context of the P4Planet co-programmed Partnership are industrial clusters that realise lighthouse projects in industrial and industrial-urban symbiosis and circularity of materials and resources. These projects contribute significantly: to the reduction of CO_2 emissions, increases in energy and resource efficiency, gaining independence from fossil-based resources, and to the reduction of waste that is incinerated or landfilled. H4C are focal points for the implementation of the technologies that are developed by P4Planet, with a focus on cross-sectorial approaches, i.e. industrial symbiosis, industrial-urban symbiosis and circular economy, in a coordinated regional setting.

Regional implementation will help to accelerate the deployment of cross-sectorial innovations by involving all necessary stakeholders and maximising the synergies of different funding schemes. This will lead to sharing of flows of energy and materials, data, services, and infrastructures and to joint development and implementation activities. H4Cs can be realised around infrastructures, for example for hydrogen or CO_2, and play a crucial role in the sharing of knowledge and the creation of specialised ecosystems.

The circular economy – building value chains for the upcycling of waste to produce feedstock for the process industries –faces significant technological and financial challenges and different waste streams require different solutions. Often solutions will cover a large geographic area in order to collect enough of a specific material for plants that is economically and environmentally attractive. While collection, dismantling, sorting and separation systems will be local or regional, further steps will be performed by relatively few large plants, be it the production of steel from scrap or of chemical feedstock from plastics. H4C may cluster waste treatment facilities with processing plants to realise synergies and become the "spider in the web" of large value chains.

The high complexity of building symbiotic solutions involving the process industries, other sectors and regional stakeholders makes their realisation challenging in the current situation:

- Industrial and industrial-urban symbiosis with the goal to physically connect processes between plants of different ownership and from different sectors and with specific regional infrastructures carries high promise for improved energy and material efficiency as mentioned in section 2.3. However, the urgency of the climate goals pushed the priorities of many companies to tackle transformations and electrification of their own processes first, which promises a higher impact in the short term and is easier to realise.

- A second aspect is the current uncertainty about which streams will be available and what will be their variations over time in the future when completely new technologies are implemented which generate other by-products, waste streams, energy demands and surplus energy. New technologies may need to be developed to specifically couple new streams of materials. This is amplified by the sense of uncertainty regarding the future of certain production processes in Europe in general. A pre-condition for cross-company symbiotic projects is a stable environment. Also, models for the joint and fair sharing of resources and the operation of resource networks under the conditions of increasing variability of raw materials, throughputs and customer demands have to be developed that consider the legal framework of anti-trust regulations.

The implementation of H4C is a long-term process that requires coordinated actions from many participants, commitment from the private sector and regional authorities, and some sort of facilitation structure. Exchange of best practices among the different hubs and initiatives is a key factor for success which has led to funding of two Coordination and Support Actions (CSAs) within the P4Planet portfolio to create a Community of Practice of H4C in Europe.

The concept of H4C has received a lot of attention and similar initiatives have been started in Europe, supported by other programmes, such as Green Deal Call 3.2, issued in 2019 on circular territorial systemic solutions, which resulted in four funded projects with a budget of € 20 million each. The Circular Cities and Regions Initiative (CCRI) was started in parallel, focusing on circular transition from the perspective of cities and regions where the production sector is only in focus in some cases. The Horizon Europe Mission on Climate-neutral and Smart Cities includes measures to achieve climate neutral city quarters but so far has not addressed industrial production within cities. Several regions started to mobilise stakeholders in so-called circular hubs or valleys to exchange knowledge and promote circularity in their regions, often with a broad focus that includes sharing, repair, and reuse of products and components, product design, and specific solutions for special waste streams.

The H4C Community of Practice has started to support the development of H4Cs with the two CSAs working together to provide a knowledge platform and build a community that connects experts and practitioners and helps them to replicate best practices. Several P4Planet calls for Innovation Actions related to H4Cs were issued and the first projects addressing connected processes, water and circular value chains have started. These projects address technology developments and demonstrations towards the climate ambition, water treatment based on case studies between industrial and urban areas, and recycling-based solutions to fulfil the circularity ambition.

Future funding for H4C should focus on strategic collaborations leading to demonstrators at industrial scale in industrial environments, first going up to TRL 7, with a plan to mature the technology beyond this level with other sources of funding. These demonstrators must be lighthouses for closing material loops and improving resource, material and energy efficiency that are deployed in a regional context. In the area of Circular Economy, the funding of H4C should support the development and deployment of cross-regional systemic solutions, starting with regional demonstrators. Calls may focus on specific streams of materials or energy with a high impact and potential for reproduction in other regions. Flexibility in project volumes is desirable. H4C could be combined with Hydrogen Valleys or other large infrastructure projects to exploit synergistic potentials.

The H4C Community of Practice must be made sustainable in the long term, so that the knowledge platform continues to be updated and maintained.

The KPI of the P4Planet Partnership is to launch 25 new H4Cs up to 2030.

4.2. Targeting deployment of innovations

P4Planet has the ambitious target to demonstrate at TRL 7 a full set of technologies for reaching the EU targets for climate neutrality, circularity of materials and industrial competitiveness by 2030 if they are rolled out broadly. P4Planet and its predecessor SPIRE have already developed a large portfolio of technologies at TRL 6 and 7 and an impressive number of these have been demonstrated at different scales as documented in the recent European Commission report[7]. The goal of P4Planet is that these demonstrators lead to First-of-a-kind industrial scale demonstrators and commercial deployments (FOAKs). The progression from the project outputs to become FOAKs is currently under detailed analysis by A.SPIRE. A preliminary analysis shows that there is a need to increase the speed of implementation of the new technologies and to overcome barriers that prevent this from happening, especially in view of the 2030 and 2040 targets.

In all sectors, including the process industries, the amount of time and effort needed to bring an innovation to the next level of TRL increases significantly from low to higher TRLs. On the other hand, the risk that an innovation turns out to be not practically feasible decreases along the TRL scale. Therefore, a broad range of ideas and technologies has to be explored at TRL 3 - 5 to fill the innovation pipeline and address challenges for which no current solutions are available yet. P4Planet has maintained and will continue to ensure a sound balance between research and innovation that provides the basis for future implementations of technologies (aiming at TRL 5-6, i.e. Research and Innovation Actions (RIAs)) and projects that advance technologies further towards commercialisation and deployment (Innovation Actions, TRL 6-7).

Currently, despite the large investments by industry into technologies that reduce carbon footprints and lead to a circular economy, the deployment rate of process innovations is still too slow in view of the challenging goals defined for 2030 and 2040. Measures are necessary to enhance the speed of maturation of the technologies supported by P4Planet under Horizon Europe so that the deployment or commercialisation phase is reached earlier, and the deployment rate is higher. Our goal is that the innovations developed by projects funded through P4Planet deliver their full possible impact within only a few years after the completion of Innovation Actions.

Reaching this goal depends on two factors: on the design and execution of the research and innovation projects, and on the regulatory and economic framework conditions, incentives, market situation, business priorities, and social and political acceptance.

For further progress towards deployment at scale or commercialisation of technical solutions that have reached higher TRLs with the help of P4Planet funding, a set of necessary conditions must be met:

- Sufficient maturity of the technology with a positive LCA.

Positive technological results at TRLs up to 6 (in lab or pilot-plant environments) are a necessary but not a sufficient precondition for successful demonstrations at TRL 7, i.e. in an industrial environment, and for further upscaling and rollout of technologies. That a technology works “in principle” does not mean that it can be integrated into a real industrial environment with non-ideal feedstock and provides the intended benefits under such conditions. Long-term process stability, low requirements for maintenance, ability by the operators to handle the innovation are further aspects that must be tackled as early as possible. For example,, small amounts of additives or impurities can accumulate or interact negatively with other components, so that the innovative technology cannot be deployed on industrial scale. These aspects should already be addressed in Innovation Actions. The LCA must include the full lifecycle of the raw materials and required additional materials and of the products and waste streams.

- Business case and ownership taken by a company ready to invest in it.

The progress of innovations to TRLs of 7 and higher, in particular to large-scale pilot demonstrations in an industrial

[7] European Commission, Directorate-General for Research and Innovation, Scaling up innovative technologies for climate neutrality – Mapping of EU demonstration projects in energy-intensive industries, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2777/926968

environment, requires the involvement and dedication of the end users and of commercial technology providers. The innovations must fit into their business and technology strategy and must be supported by the leadership of the companies so that obstacles are overcome by joint efforts.

- Stable and favourable framework conditions, access to sufficient amounts of affordable renewable energy and infrastructures as a prerequisite for deployment and impact.

Investments in new technologies require that they are financially attractive, i.e. a sufficient financial gain can be expected. Innovative technologies developed by P4Planet that do not meet this requirement for investments will remain blueprints but may be reviewed sometime in the future. As the investments are high and based on anticipated returns on investment over long periods of time - at least 10, often more, years - long-term stability of regulatory conditions, incentives, and protection against unfair competition from abroad that is not subject to the same regulations, or compensation of these disadvantages, is needed, as foreseen for example by the CBAM. Measures such as green procurement or Public Procurement of Innovative Products (PPPI)[8] can be helpful to overcome price thresholds, as sustainable products will be more expensive at the beginning. The transition to the use of electric power requires its sufficient and stable availability at prices that lead to competitive production. Plans for the further extension of the production of renewable power and for the realisation of distribution grids, for example for hydrogen or for CO_2, must be coordinated Europe-wide. Price mechanisms in the markets for electricity and other carriers of energy must be fair, attractive for the producing companies, also for medium-size producers, and stable and predictable to ensure the amortisation of investments.

- De-risking innovation via priority setting and co-financing opportunities and incentives.

The ERA industrial technology roadmap for low-carbon technologies in energy-intensive industries[9] shows that the biggest investment gap needed to reach decarbonisation targets concerns investments for industrial-scale demonstrators and first-of-a-kind plants. Innovations at TRLs above 7 require large investments and carry a significant technical and economic risk. Therefore, co-financing and blended funding models are necessary to de-risk them. The links to national and regional programmes must be strengthened in order to align with strategic objectives and provide support opportunities for the most impactful innovations. It might be helpful to give support to innovations that are generated within running Innovation Actions to prepare applications for further funding and investment schemes, such as Innovation Fund, Invest-EU, European Investment Bank (EIB) programmes, and further private investments. Projects boosting Horizon Europe Innovation Fund synergies in the areas of Energy Intensive Industries and Carbon Capture and Utilisation have been financed within the 2023 work programme and already started. While de-risking investments is important, the basic condition for investments remains their long-term financial attractiveness.

The range of technologies that are proposed and developed by the P4Planet projects at low to medium TRLs (4-6) is typically broader than those that are further developed towards higher TRLs because it is inevitable that there is some attrition due to technological reasons or economic and other framework conditions. The goal of the further development process of promising innovations is to drive them towards implementations at industrial scale and commercialisation. Innovation Actions (IA) should therefore be based on successful demonstrations of the technologies at a relevant scale and tackle the key obstacles to the subsequent industrial take-up of the developments after the successful conclusion of the projects. Many projects funded under SPIRE calls have achieved this target and have led to new products and large-scale demonstrators.

Regarding funding mechanisms within Horizon Europe aiming at TRLs up to TRL 7, the following suggestions are made:

- It remains important to fund research and innovation projects aiming at middle TRLs (5-6) to investigate the feasibility of new ideas, technologies, and concepts, to fill the innovation pipeline and to address issues for

[8] Horizon Europe funding for PCP and PPI | Shaping Europe’s digital future (europa.eu)
[9] European Commission, Directorate-General for Research and Innovation, ERA industrial technology roadmap for low-carbon technologies in energy-intensive industries, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2777/92567

which no solution is currently available. Demonstrators at smaller scales should provide evidence of the potential for success.

- Innovation Actions are crucial to bring technologies close to deployment and commercialisation. In Innovation Action proposals, verifiable evidence must be provided that the technologies have reached middle TRLs before an IA starts, and there must be a clear plan how to advance to the point where the technical and economic conditions for deployment are met, with a quantitative substantiation of the starting point and the targets of the IA. This may already include the consideration of follow-up or additional funding by the companies involved or national and regional or European programmes after the successful completion of the IA.

  Often progression to demonstration at industrial scale requires substantial additional efforts beyond that funded by the projects. It is therefore crucial that within IAs leadership for the innovations is taken by the industrial partners and that they are ready to invest significant resources into the further maturation of the technologies. Demonstrations should take place over sufficiently long periods in an industrial environment or under conditions which are similar to production environments.

- In the process industries, the producing companies may not want to play the role of technology providers to other producers in the same or other sectors themselves, and innovations are often commercialised by engineering companies or equipment manufacturers. Therefore, the participation of commercial technology providers, from SMEs to large contractors, in Innovation Action consortia should be stimulated, and a clear business strategy for the integration of the innovations into their portfolios should be outlined. Both in RIAs and IAs, doors should be kept open and possibly also flexible funding should be provided for technology providers, especially SMEs, to join the consortia during the execution of the project if they are interested to take over the technologies after the project concludes.

An additional set of actions will be envisaged both from the private and the public side to support the process of the deployment of research and innovation solutions for climate neutrality and circularity of the EU process industries. Such actions should seek to connect and maximise synergies with other relevant public and private actions. Areas that might be targeted could follow the issues identified as deployment barriers during the ongoing activities and pointed out in surveys by project participants. For example, these include:

- Further mapping and monitoring of the deployment of innovative technologies for the energy intensive industries and of the maturity status of technologies and their expected evolution over time. The European Commission has started building a database of net-zero technologies that are demonstrated around Europe under EU-funded projects. A first overview has been published in the report 'Scaling up innovative technologies for climate neutrality' referenced earlier and a mapping of these demonstrators around the EU is also available in an online tool. This list of demonstrators will feed into the upcoming INCITE[10] initiative.
- Boosting synergistic use and coordination of national, regional and EU funding and exploring ways on how to increase the synergistic use of the EU and national/regional innovation programmes for bridging the gap between research and innovation and deployment in line with P4Planet Impact Panel objectives. For example, A.SPIRE is now a partner in two CSA consortia aiming to mobilise the SPIRE and P4Planet innovation pipeline towards the Innovation Fund.
- Targeted actions for creating and supporting markets for climate-neutral products through demand side measures such as innovation procurement or standards, as well as empowering customers and consumers.
- Joint analysis of regulatory barriers and related issues such as permits that can delay or even block not only large-scale deployments but also the realisation of demonstrators within P4Planet projects.

[10] www.oecd.org/chemicalsafety/risk-management/presentation-emerging-techniques-for-pollution-prevention-control-simon-gutierrez-alonso.pdf

- Participation in the cross-Partnerships spaces: Clean Planet Inter-Partnerships Assembly and the Partnerships Knowledge Hub.

Further collaborative dialogue is in place with Partnerships and Initiatives representing different parts of the value chain when relevant synergies to address complementarities are identified. Alignments with Clean Steel are achieved through dedicated meetings following the agreement reflected in the “Joint Declaration from A.SPIRE, EUROFER and ESTEP” signed in 2019. Alignments with Built4People are reflected in the document “B4P & P4Planet Synergies document 2022-25” signed in 2023. The “Joint declaration from AMI2030 and A.SPIRE” was also signed in 2023. International collaboration is tackled through participation in the Mission Innovation Net-Zero.

Striving to rethink the interaction with the energy sector, alignments have been reached with: the Clean Hydrogen JU through regular meetings when the respective work programmes are developed; with the Clean Energy Transition Partnership (CETP) to strive for alignments to foster deployment; and with SET-PLAN IWG6, co-chaired by A.SPIRE since 2014. Besides contributing to the SET PLAN #6 action plan, A.SPIRE is currently part of the CSA consortium managing the Secretariat of the Group.

The measures discussed in this section support the achievement of KPIs 7 – 10 of the P4Planet Partnership (see table in Appendix 1).

4.3. Preserving knowledge

As discussed above, it is to some extent unavoidable that the development of a technical innovation faces challenges that are hard or currently uneconomic to overcome, and the development process of some innovations may be discontinued due to lack of funding or industrial support. However, these projects usually have generated valuable insights and knowledge that can be used outside the original consortia to help build new technologies. Currently, this knowledge is very difficult to access and is not promoted systematically after the end of projects. In many cases, it is not possible to judge from the available public information to what extent a development was successful and what obstacles were encountered. Mandatory mechanisms for the documentation of the outcomes of projects should be developed and funding should be provided for an infrastructure that preserves this knowledge and continuously updates it, as is currently done by the H4C Knowledge Platform in the domains of industrial and industrial-urban symbiosis and circular economy.

5. Conclusions and outlook

The P4Planet partnership aims to achieve three general objectives:

1. Contribute to the climate neutrality of the overall European economy by bringing technological and non-technological innovations to readiness for subsequent deployment.
2. Develop and deploy sustainable circular solutions through technological and non-technological innovations and cross-sectoral collaboration.
3. Strengthen the competitive and leadership position of the European process industries at global level.

To achieve these goals simultaneously is a tremendous task that requires nothing less than to completely rebuild the European process industries in the coming decades. New carriers of energy have to be introduced, new materials have to be designed and produced, new production processes have to be established. The whole system of exchanges of energy and materials between different plants, sites, and sectors that has evolved over a century based on the input of fossil resources and unrestricted emissions of CO_2 will have to be redesigned. Production processes that have dominated over decades or even centuries will have to be replaced by climate neutral ones. At the same time, world-wide competition is sharper than ever; other economies are eager to take over productions that are still based in Europe, and the procurement of many raw materials will become ever more challenging. The sheer size of many plants and processes and the large amounts of materials and energy that are transformed in these plants make fast changes economically and technically risky. The present production technology represents an enormous invested capital and therefore care must be taken to transform the existing plants in an economically viable manner and to integrate them into new production systems.

In consequence, the process industries are under enormous pressure to meet the climate and circularity targets on the one hand and to stay competitive on the other. The events of the last years have also drastically exposed the risks of not maintaining an industrial base that is able to produce key materials for the needs of society in Europe. Hence the survival and long-term resilience of sustainable process industries in Europe is more important than ever and must be harmonised with climate and circularity goals.

Through the projects that have already been funded under the P4Planet partnership, a large number of significant innovations have been generated and demonstrated at different scales. The project outcomes have already made significant contributions to the future large-scale reconfigurations that have been sketched out above.

In this period of transition, intense research and innovation activity will be needed over a long period of time to provide the technological foundations for climate neutrality, circularity, and competitiveness. There is a continuous need for the collaborative cross-national and cross-sectorial development of technologies at lower TRLs. At the same time and at an even higher speed, promising developments have to be pushed to deployment: from inventions to innovations.

The process industries and the research and innovation ecosystem around them are fully committed to meeting the climate targets and to substantially increasing the circularity of materials. They support the goals of sustainability, resilience and human-centric industry that have been outlined under the title of Industry 5.0. The implementation of these innovations requires stable and favourable boundary conditions. Regulations should concern targets and economic incentives related to outcomes, for example measured by sustainability indicators, but not prescribe or restrict the scope of technical solutions. Energy from renewable sources must become available at a fast pace and at a cost which is bearable in view of international competition. The huge upcoming transition requires a well-coordinated approach between many sectors to establish a harmonised path to the European process industries of the future along which all players can survive economically. Given the large scale of the necessary investments and the uncertainties related to the implementation of new technologies, de-risking of investments will continue to be necessary.

P4Planet is confident to meet the ambitious technological goals that were formulated at the beginning of the partnership. But this is only the first step. The path to climate neutrality and full circularity is a long and difficult one, and large improvements in energy and material efficiency have to be achieved to make climate neutrality and circular solutions economically viable in a world where there will not be an infinite supply of renewable energy at low cost in the medium-term future. In a changing world, the European process industries will become climate neutral, resilient, circular, and human centric, and minimize their environmental impact based upon continuous research and innovation in new processes and products. The Processes4Planet PPP makes a key contribution to securing the future of the European process industries as a major employer and key pillar of the wealth and stability of Europe. New challenges have arisen on top of those which were evident when the PPP was launched. By coordinated efforts of the private and the public side, we will meet them.

APPENDIX 1:

Table of P4Planet KPIs

General Objectives	Specific objectives	Operational objectives	KPIs		Objective by 2030
CLIMATE					
GO1.- Developing and fostering the deployment of climate neutral solutions	**SO1.-** Integrating Renewable energy	**OO1.-** Develop new electrified processes and Energy efficiency, ensuring process flexibility and capturing the full potential of renewable energies	KPI 1	CO2 Eq. emission reduction by integration of renewable energy & energy efficiency**, measured on a relevant* number of demonstrators**	100% of total CO2 eq emission reduction potential demonstrated through R&I projects at TRsL7 **
		OO2.- Replace fossil fuels and feedstock by Renewable H2 and biomass in processes			
	SO2.- Reduce emissions through CO/CO2 capture and use	**OO3.-** Develop new efficient CO/CO2 Capture and purification technologies	KPI 2	CO2 Eq. emission reduction through CO2 Capture and Use measured through a relevant* number of demonstrators**	100% of total CO2 eq emission reduction potential demonstrated through R&I projects at TRL7 **
		OO4.- Develop efficient CO2 valorisation routes to chemicals, minerals and fuels			
CIRCULAR					
GO2.- Developing and deploying industrial solutions aiming at closing the energy and feedstock loops	**SO3.-** Ensure full circularity and overhaul the use of waste	**OO5.-** Design processes for maximum resource efficiency, including the development of materials for circularity	KPI 3	Waste**** reduction measured through a relevant* number of demonstrators**	80% of Wastes reduction potential demonstrated through R&I projects at TRL7**
		OO6.- Develop new processes for circularity of secondary materials from wastes/residues for all industrial processes	KPI 4	Secondary materials use intensity measured through a relevant* number of demonstrators**	80%Secondary materials re-usable potential demonstrated through R&I projects at TRL7**
		OO7.- Develop new processes to ensure full valorisation of waste-water, recycled water, energy and solutes recovery	KPI 5	Water reused/ recycled through Energy and solute recovery measured through a relevant*-	90% of waste water reused/Recycled potential demonstrated at through R&I projects at TRL7**
		OO8.- Seed H4C's to foster circularity within and beyond process industries	KPI 6	Nbr of H4C seeded through P4PLanet projects across EU regions / sites	25 H4Cs launched into the process of development (*****)
COMPETITIVENESS					
GO3.- Fostering the achievement of a global leadership in climate neutral and circular solutions, accelerating innovation and unlocking public and private investment	**SO4.-** Moving towards commercially viable climate neutral and circular industry solutions	**OO9.-** Drive the Partnerhip's innovation portfolio up to FOAK's in order to derisk investment	KPI 7	Marbles (First-of-a-kind plants at TRL9)	Launch 15+ marbles integrating the solutions developed through P4PLAnet profolio towards the 100% target+
			KPI 8	Significant innovations developed	60 Significant innovations reaching TRL 7-8, of which a substantial part will lead to FOAKs
			KPI 9	CAPEX & OPEX reduction through the new innovations	CAPEX & OPEX reduction through the new innovations
	SO5.- Fostering new skills & jobs and reducing barriers for market uptake	**OO10.-** Foster new framework conditions to generate a market for climate neutral	KPI 10	Impact in SMEs through the projects and the H4Cs	Impact in SMEs through the projects and the H4Cs
		OO11.- Foster new skills and types of jobs and business development, including SMEs, through P4Planet programs and H4Cs	KPI 11	Nbr of new jobs and job profiles	20 new types of skills and jobs for operators and high-skilled profiles, of which at least 10 integrated in specific academic curricula and 10 integrated company training programs.

APPENDIX 2:

A.SPIRE Governance and Advisory Structure