INTEGRATED SET PLAN

SET Plan Action 6 on Energy Efficiency in Industry

Implementation Plan
Revision 2021

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endorsed by the SET Plan Steering Group

Increasing efforts to make EU industry less energy, resource and emissions intensive and more competitive

PURPOSE OF THIS DOCUMENT AND AIMS OF ACTION 6

The European Strategic Energy Technology Plan (SET Plan) aims to accelerate the transition towards a climate neutral energy system through the development of low-carbon technologies. It brings together the European Commission, EU Member States and other interested countries, industry and the research community to coordinate research efforts and investments. The SET Plan identifies ten actions for research and innovation. **Action 6 is dedicated to making EU industry less energy, resource and emissions intensive and more competitive**.

This document is **the 2021 revised Implementation Plan (IP) for Action 6.** It aligns Action 6 with recent research and innovation (R&I) developments and policy changes such as the European Green Deal. The IP draws on the expertise of industry stakeholders to set out priority R&I activities and collectively agreed targets within the Action's two cross cutting areas (Heat & Cold and Systems) and four sectorial areas (Cement, Chemicals, Iron & Steel and Pulp & Paper).

Technologies and strategies in these priority areas are constantly evolving. The IP is intended to provide an indication of the current status as of August 2021. Further updates in separate documentation may be added to the Action 6 section of the SETIS website, as appropriate.

Each SET Plan Action has an **Implementation Working Group (IWG)** made up of country, industry and research representatives to advance the actual realisation of its IP.

Member States and non-EU SET Plan countries will have a fundamental role alongside the European Commission to work in collaboration with industry to facilitate the deployment and market penetration of emerging technologies. This document collates information from industry leaders to support governments in Action 6 areas in the following ways:

- Creating a shared understanding of R&I challenges and opportunities;
- Providing an overview of priority areas to focus R&I efforts for energy intensive industry;
- Identifying priority activities where funding should be targeted (facilitates road-mapping by EC and SET Plan countries);
- Enabling national governments to make informed policy decisions that further support technology development and deployment in these areas.

This document is structured into the following sections:

- **Section 1** introduces the **IWG structure**;
- **Section 2** presents relevant the **policy context** relevant to SET Plan;
- **Section 3** defines the **expanded scope of Action 6**;
- **Section 4** details the **rationale** behind the selection of the included industry sectors;
- **Section 5** provides an outline of **R&I Activities** required to achieve the ambitious targets set by the European Commission for Action 6 industries by 2030 and 2050;
- **Section 6** defines **targets** for each priority R&I area;
- **Section 7** summarises Action 6's **next steps;**
- Finally, the **Annexes** provide greater detail on R&I activities (in fiches), and an overview of the Action 6 IWG membership.

TABLE OF CONTENTS

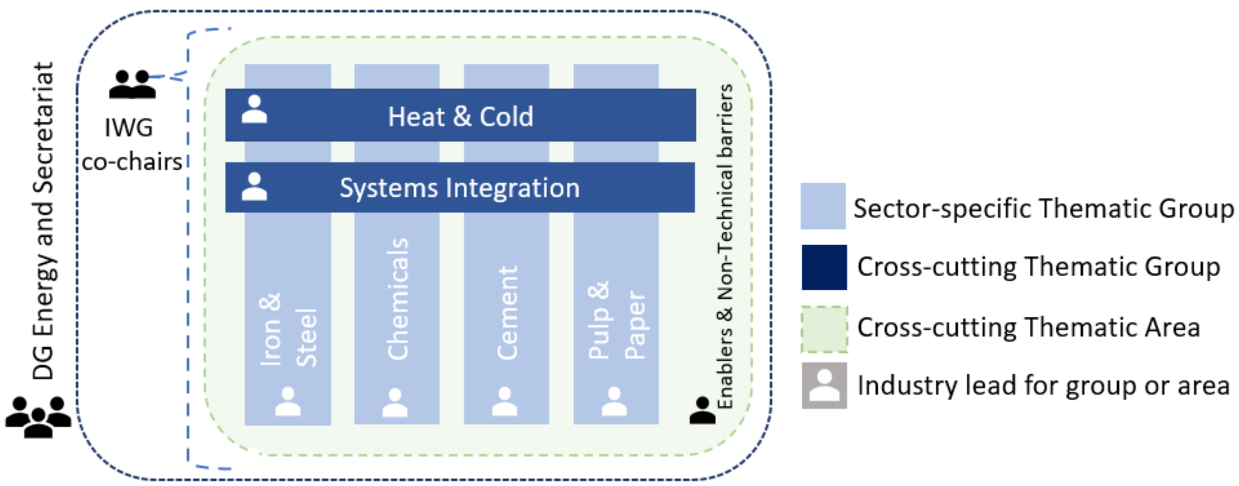
1 INTRODUCTION TO THE IMPLEMENTATION WORKING GROUP 6

Implementation Working Groups (IWGs) are established to advance the SET Plan Action Implementation Plans (IPs) with the aim of reaching technology targets collectively across SET Plan countries and to place Europe at the forefront of the next generation of low carbon technologies. The Action 6 IWG is specifically dedicated to making EU industry less energy, resource and emissions intensive and more competitive .

The Action 6 IWG (IWG6) includes national representatives from 20 SET Plan countries and 23 stakeholders from industry, research and academia. As can be seen in Figure 1-1, the IWG is structured around **six Thematic Groups** which cover specific sectors and cross cutting topics that relate to all high energy intensive activities. IWG members indicate the thematic groups in which they wish to participate.

The IWG6 also comprises **two thematic areas**. These are the **enabling technologies** which are seen as essential in supporting sector and technology progress towards Action 6's aims (e.g. the use of low carbon hydrogen to decarbonise certain industrial processes), and the **non-technical barriers** which need to be overcome along technology pathways to widespread deployment (e.g. overcoming high upfront costs of emerging technologies). Each Thematic Group and thematic area has an industry Lead. The IWG is co-chaired by a Country representative and a representative from industry.

Figure 1-1 IWG Structure



Since the establishment of Action 6 in 2017, the work of the IWG has delivered the following key achievements:

- Approved and adopted the first Action 6 IP in 2017 which was a source of inspiration for the design and implementation of several national R&I programmes;
- Delivered Action 6 R&I knowledge sharing workshops (in 2018 and 2019) with IWG Country representatives and industry. These have led to the development of 40 project proposals in Action 6 industries and the sharing of information between SET Plan countries on R&I programme and cooperation models;
- Provided expertise to inform EU R&I funding topics on industrial heat recovery under multiple programmes including Horizon 2020 and Horizon Europe, while ensuring they complemented the coming Processes4Planet Private Public Partnership;
- Contributed expert knowledge to the EC Clean Energy Transition - Technologies and Innovation Report on industrial heat management; and
- Contributed indirectly to the upcoming Clean Steel partnership under Horizon Europe (HEU) and to the visibility of national projects and their application for funding under the Innovation Fund, through coordination of Action 6 Iron and Steel R&I activities.

2 POLICY CONTEXT

The **Energy Union Strategy**[1] was launched in early 2015 as part of the 10 key priorities of the Juncker Commission. The strategy is built upon five interrelated pillars for accelerating the decarbonisation of the European energy system cost-effectively. The SET Plan was recognised as one of the primary tools to delivering goals under the strategy's pillar on research, innovation and competitiveness, through contributing to the cost reduction and improvement in performance of low carbon energy technologies through impactful synergistic innovation actions.

The European Commission Communication for an **Integrated Strategic Energy Technology Plan**[2] identified ten priority actions to accelerate the energy system transformation, through coordinated or joint research activities and investments on technology pathways between European countries, private stakeholders (including research and industry) and the European Commission. Out of the ten priorities, Action 6 is aimed at the continuation of our efforts to **make EU industry less energy intensive and more competitive**.

The **European Green Deal,**[3] announced in 2019, supersedes previous Commission commitments on tackling climate and environmental-related challenges. It outlines plans to make the EU's economy sustainable and increases climate ambition throughout the EU with the long-term goal of becoming climate neutral by 2050. The European Commission proposed legally binding legislation, called the 'Climate Law', to ensure that all EU Institutions and Member States commit to this target and are responsible for aligning all policies accordingly. As part of the European Green Deal, a short-term emissions reduction target of 55% below 1990 levels by 2030 has also been established.

The European Green Deal also emphasises that the transition needs to maintain competitiveness of energy-intensive industries, including those covered by Action 6; recognised as 'indispensable' to the EU's economy. Furthermore, the European Green Deal sets out a number of targets and actions that relate to Action 6, through the following strategies and initiatives:

- EU Industrial Strategy[4]
- Chemicals Strategy[5]
- EU Strategy on Clean Steel[6]
- Energy System Integration and Hydrogen Strategy[7]
- Circular Economy Action Plan[8]
- Zero carbon steel-making processes by 2030[9] (proposal for the amendment of 2008/376/EC)
- EU Forest strategy[10]
- Other relevant upcoming initiatives include Sustainable Products Initiative, Renewed Sustainable Finance Strategy and the Carbon Border Adjustment Mechanism.[11]

The **EU Industrial Strategy**, first published in 2020 and subsequently updated in May 2021 (in light of the COVID-19 pandemic), sets out an approach to drive the transformation to a more sustainable, digital, resilient and globally competitive economy in Europe. This includes supporting industry towards climate neutrality, outlining that reducing emissions across industry will depend on an 'energy efficiency first'

[1] (COM (2015) 80 final) https://eur-lex.europa.eu/resource.html?uri=cellar:1bd46c90-bdd4-11e4-bbe1-01aa75ed71a1.0001.03/DOC_1&format=PDF; (COM (2019) 175 final) https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52019DC0175
[2] (C(2015) 6317 final) https://setis.ec.europa.eu/system/files/integrated_set-plan/communication_set-plan_15_sept_2015.pdf
[3] (COM (2019) 640 final) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640
[4] (COM (2020) 102 final) https://ec.europa.eu/info/sites/info/files/communication-eu-industrial-strategy-march-2020_en.pdf;
[5] (COM (2020) 667 final) https://ec.europa.eu/environment/pdf/chemicals/2020/10/Strategy.pdf
[6] COM(2021) 350 final)https://ec.europa.eu/info/sites/default/files/swd-competitive-clean-european-steel_en.pdf
[7] (COM (2020) 301 final) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301
[8] (COM (2020) 98 final) https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN
[9] (COM (2020) 320 final) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0320
[10] (COM (2019) 352 final) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0352
[11] These policies are still in consultation as of March 2021 and do not have published EC communications

principle and a secure and sufficient supply of low-carbon energy at competitive prices. The update additionally adds new support measures for the digital and green transitions

The energy efficiency of EU industry is mainly driven by **four key pieces of EU legislation**:

1) the **Energy Efficiency Directive** (EED) (2012/27/EU) and its 2018 amendment (2018/2002), which covers a group of binding measures to reduce total energy consumption across the EU and Member States *(planned review in 2021[12])*;
2) the **EU Emission Trading System** (ETS) **Directive** 2003/87/EC, which sets emissions allowances for industry installations of certain size and sector while providing the ability to trade emissions below or above the allowed amount to other installations in the carbon market *(undergoing review in 2021[13])*;
3) the **Industrial Emissions Directive** (IED) (2010/75/EU), which requires that the BAT (Best Available Techniques to reduce emissions and environment impact, including the reduction of energy consumption) conclusions shall be the reference for setting the permit conditions of the installations covered by the IED *(undergoing review in 2021)*;
4) the **Eco-design** (2009/125/EC) and **Energy-labelling Directives** (2017/1369), which sets the minimum energy efficiency standards and energy labels to support the development and market uptake of energy efficient products.

At the end of 2019, Member States submitted integrated **National Energy and Climate Plans (NECPs)** for the period 2021-2030. NECPs contain detailed strategies on how Member States will comply with the EU's 2030 Climate Target Plan. They must also address energy efficiency, GHG emissions reductions, renewables and R&I. The NECPs provide information relevant to public and private investment plans, in tandem with the EU funds earmarked for investments into climate solutions. Member States must also submit revised **National Energy Efficiency Action Plans (NEEAPs)** every three years as part of the Energy Efficiency Directive. These detail national energy consumption estimates and strategies to achieve reduction targets.

3 SCOPE OF THE IMPLEMENTATION PLAN

Following the endorsement of the Declaration of Intent by the SET Plan Steering Group in 2016, the first version of the IP was endorsed in September 2017. This document defined *priorities* and *activities* that would contribute to the targets of Action 6 through European and National projects conducted through cooperation between several EU Member States and SET Plan Associated Countries (jointly referred to as "Countries") in the field of energy, resource and emissions efficiency in industry.

To continue the execution of the IP, the structure of the working group evolved into the current **Implementation Working Group (IWG6)** who developed and validated this revised IP over the course of 2020 - 2021. The revised Action 6 IP and the IWG have increased in scope since its inception in the following ways:

- Inclusion of 'Cement' and 'Pulp & Paper' as new sectors to aid collaboration and enable their progress towards energy efficiency and emissions reductions;
- Expansion in focus to include emissions reductions as well as energy and resource efficiency to reflect changes in EU policy framework (such as the European Green Deal);
- Inclusion of 'Enablers' and 'Non-Technical Barriers' as additional cross-cutting thematic areas of focus for the full IWG;
- Adoption of a longer-term perspective to consider market uptake of innovative solutions and R&I activities beyond 2030.

The membership of the IWG now comprises of **19 SET Plan countries** (Austria, Belgium, Switzerland, Cyprus, Czech Republic, Germany, Spain, Finland, France, Ireland, Italy, Latvia, Netherlands, Norway, Poland, Portugal, Sweden, Slovakia, Turkey), **industrial stakeholders from 4 sectors** (Cement, which is part of the non-metallic minerals sector, Chemicals, Iron & Steel, and Pulp & Paper) and **cross-cutting**

[12] Part of the European Commission's Fit for 55 package (https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541)
[13] Part of the European Commission's Fit for 55 package (https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541)

technology areas (Heat & Cold, Systems, and enabling energy technologies) as well as **research institutions.**

4 RATIONALE FOR THE SELECTION OF INDUSTRIAL SECTORS

To maximise the impact of R&I, there is a need to prioritise sector-specific technologies with the highest potential for reducing carbon emissions and energy and resource consumption. The aim of the prioritisation is to allow more specific focus on identifying and implementing definitive and coordinated actions. This section presents the rationale.

In the first version of the IP (2017), two sectors (Iron & Steel and Chemicals) were identified as having the highest potential. Subsequently, one additional sector (Pulp & Paper) and a component of the non-metallic minerals sector (cement) have been included that have potential to contribute to the wider energy efficiency and decarbonisation scope of Action 6 and to participate in industrial symbiosis schemes together with the first two sectors. Table 4-1 presents current and projected energy consumption and carbon emissions from each sector to provide context on each.

Table 4-1 Sector Emissions and Energy Use for EU-27 and the UK

	Carbon emissions/ year [Mt CO_2 eq.][14]	Energy consumption [Mtoe/y][15]	Technical savings potential by 2030 [Mtoe/y][16]	No. employed[17]	Gross added value [M€][18]	Energy intensity [ktoe/M€][19]
Source year	**2020**	**2017-2020[14]**	**2017**	**2017-2020[16]**	**2015-2020[17]**	**2015-2020[18]**
Cement	118	13	*n/a*[20]	35,400	5,000	2.6
Chemicals	140	51.5	16.5	1,100,000	80,000	0.6
Iron & Steel	201	50.8	16.3	330,000	24,000	2.1
Pulp & paper	31[21]	34.3	7.2	182,000	21,000	1.6
Four sectors total/average	490 (total)	150 (total)		1,647,400 (total)	130,000 (total)	1.7 (average)
Whole industry total / average[22]	**864 (total)**	**261 (total)**	**71.7 (total)**			

Activities in other sectors beyond these are not excluded from Action 6. If a number of stakeholders and/or Countries wish to cooperate on specific actions, they are invited to make such proposals. Other sectors will also benefit from actions addressing the cross-cutting technologies (Heat & Cold and Systems).

5 OVERVIEW OF PRIORITIES AND ACTIVITIES

With respect to the thematic areas, this document presents a summary of priority areas for technological R&I within Action 6 industries. It does so without prescribing importance or specific order of any one of these priority activities over others listed.

[14] Agora Energiewende and Wuppertal Institute (2021): Breakthrough Strategies for Climate- Neutral Industry in Europe: Policy and Technology Pathways for Raising EU Climate Ambition; https://www.odyssee-mure.eu/; CEPI Key Statistics 2019 and 2050 Roadmap
[15] https://ec.europa.eu/eurostat/home except cement which is sourced from Agora Energiewende and Wuppertal Institute (2021)
[16] Sum of energy saving potentials of all technically feasible technologies, regardless of economic or mutual compatibility constraints (source: ICF2015a, not endorsed by industry)
[17] The figure for cement was sourced from EUROSTAT (2017 data), Chemicals was sourced from Agora Energiewende and Wuppertal Institute (2021), Iron & Steel was sourced from Eurofer (2019 data) and Pulp & Paper was sourced from CEPI Key Statistics 2019.
[18] The figure for cement was sourced from Ecorys Competitiveness of the European Cement and Lime Sectors (2015), Chemicals was sourced from Agora Energiewende and Wuppertal Institute (2021), Iron & Steel was sourced from Eurofer European Steel in Figures 2020 and Pulp & Paper was sourced from CEPI Key Statistics 2019.
[19] Calculated by dividing the sector's energy consumption by their gross added value.
[20] Data not available at for cement sector alone.
[21] Figure is for 2019.
[22] Values for no. employed, gross added value and energy intensity have not been included to avoid discrepancies between the aggregation of industry data.

Table 5-1 Thematic Groups and prioritised R&I activities

TG	No.	Title
Heat & Cold	1.1	Heat upgrade from low to high grade
	1.2	Waste heat to power (low and high temperature)
	1.3	Waste heat to cold generation
	1.4	Polygeneration (heat, cold, electrical power) and hybrid plants integrating renewable heat
Systems	2.1	Industrial symbiosis
	2.2	Non-conventional energy sources in process industry including carbon capture and use
	2.3	Digitalisation
	2.4	Knowledge exchange, training and capacity-building
Cement	3.1	Resource efficiency*
	3.2	Energy efficiency*
	3.3	Carbon Capture Storage and Usage (CCS/U)*
	3.4	Recarbonation and mineralisation*
Chemicals	4.1	Electrification
	4.2	Integrated production of Hydrogen with low carbon footprint*
	4.3	Plastic waste as an alternative feedstock*
	4.4	CO_2 / CO as an alternative feedstock*
	4.5	Biomass as an alternative feedstock *(shared activity, see Pulp & Paper 6.6)**
	4.6	Process efficiency
Iron & Steel	5.1	CO_2 emissions avoidance through direct reduction of iron using Hydrogen
	5.2	CO_2 emissions avoidance through direct reduction iron using electricity*
	5.3	Process integration: HIsarna smelting reduction process for lowering energy consumption and CO_2 emissions of steel production
	5.4	Process integration: Top Gas Recycling – Blast Furnace (TGR-BF) using plasma torch
	5.5	Carbon Capture and Usage (CCU)*
	5.6	Circular economy*
Pulp & Paper	6.1	Integral drying and heat recovery processes*
	6.2	Paper making without water evaporation*
	6.3	Process optimisation and electrification (modular approach)*
	6.4	Mild pulping processes *
	6.5	Onsite renewable energy conversion*
	6.6	Biomass as alternative feedstock *(shared activity, see Chemicals 4.5)**

* Indicates activities that are new to the 2021 IP

These different Thematic Groups and activities do not exist in isolation from each other. All of the four sector-specific Thematic Groups are expected to benefit from technologies in the two cross-cutting (horizontal) Thematic Groups. Additionally, there are further potential interlinkages between the different sectors. Table 5-2 shows key areas of interest and synergies between these groups.

Table 5-2 Activities interlinkages

		Heat & cold	Systems	Cement	Chemical	Iron & steel	Pulp & Paper
Heat & cold	1.1 Heat upgrade from low to high grade	-	✓	✓	✓	✓	✓
	1.2 Waste heat to power	-	✓	✓	✓	✓	✓
	1.3 Waste heat to cold generation	-	✓		✓	✓ (1)	
	1.4 Polygeneration and hybrid plants	-	✓	✓	✓	✓	✓
Systems	2.1 Industrial symbiosis	✓	-	✓	✓ (2)	✓	✓
	2.2 Non-conventional energy sources including CCU	✓ (3)	-	✓	✓	✓	✓
	2.3 Digitalisation (and Integration of IT-systems)	✓	-	✓	✓	✓	✓
	2.4 Knowledge exchange, training and capacity-building	✓	-	✓	✓	✓	✓

(1) Minor requirement for cooling; (2) Some limitations due to operating safety near other sites; (3) the key link between Heat & cold and activity 2.2 are the CCU technologies

Interlinkages also exist beyond Action 6 and the nine other Actions, which together aim to boost the transition towards a complete climate neutral energy system. Action 6 is primarily focused on industry's usage of energy (and to a lesser extent its supply), while the generation, transformation, storage and wider supply of energy is covered within other SET Plan Actions. The interdependencies and interactions within these different parts of the energy system also need to be considered, for example through cross collaboration of the different SET Plan Actions.

Other SET Plan Implementation Plans will be useful resources and are available on the SETIS website.

Fiches on each of the Action 6 activity areas are available in Annex 2. These provide additional detail on the R&I activities and budget estimations where available. Due to the wide range of sectors included, there is variation in the content of the different activity proposals, in areas such as their advancement (Technology Readiness Level[23] (TRL)), budget requirements and focus (energy or emissions). These stem from variations in the composition of the sectors themselves, core processes, feedstocks and products.

5.1 Heat/cold – generation, upgrade and recovery

Thermal energy is needed in the energy-intensive industry, therefore increasing the integration of renewable energy sources and efficiency of its utilisation in industrial processes is a key factor to achieve the Green Deal goals. Heat and cold recovery and conversion technologies are instrumental for intra-plant optimisation and inter-plant integration (industrial symbiosis) to enable the cascading use of heat (or cold) between cross-sector plants in industrial parks, and within district heating/cooling networks, thus greatly reducing the overall energy consumption. A mapping of the industrial excess/surplus heat and cold, considering the proximity to users such as other industrial sites, district heating and cooling networks in EU[24] would contribute to better prioritise the related R&I programme and to the increased integration of these residual sources into heating and cooling plans.

Activity 1.1 - Thermal energy upgrade from low temperature to high temperature

Heat pumps can convert low grade heat (typically at 50°C-120°C) into higher grade heat. Commercial products exist up to supply temperatures of 160°C, but the demonstration in more industrial applications is still needed. R&I is ongoing to reach up to 200/250°C while temperatures over 250°C are more

[23] TRL scale as defined: https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf
[24] The STRATEGO project contributed to develop the mapping of industrial surplus heat/cold sources and potential users in the EU. https://www.euroheat.org/our-projects/stratego-multi-level-actions-enhanced-heating-cooling-plans/

challenging. The development of pilot (or prototype) and demonstration of innovative heat pump technologies (2-3 MW) to make cost effective use of waste heat at highest efficiencies by using advanced thermal cycles or unique concepts should be pursued.

Two R&I activities are proposed:

- Heat pumps converting low to high grade heat up to 200/250°C from TRL 5 to TRL 7 by 2025;
- Heat pumps converting low to high grade heat above 250°C starting TRL 3 to TRL 6 by 2025.

Activity 1.2 - Waste Heat to Power (low and high temperature, small and large power output)

a. *Use of low/medium temperature waste heat (120 - 350ºC) to generate electrical power at high efficiency.*

Development of pilot (or prototype) and demonstration of innovative power generation concepts, which can be combined with further cascaded heat uses when possible/relevant. R&I needs of larger units (MW's range) are different from smaller units (kW's range) and the TRL of larger units is presently higher, though the potential from smaller standardised units is very large. To make cost effective use of low temperature waste heat at highest efficiencies, several technologies, are partly complementary or competing, and at different maturity levels.

There is a need for R&I to evaluate the potential of these technologies and to move from the current low TRL (TRL 1 to 4) to TRL 4 and eventually 7 for the most promising ones. For other more established concepts achieving TRL 7 is needed, therefore the R&I activities proposed are:

- Small scale waste heat to power plants, from TRL 1-4 to 4-7
- Large scale waste heat to power plants, from TRL 4 to 7. Additional budget will be required to achieve TRL8 and 9.

b. *High temperature waste heat recovery to generate electrical power at high efficiency:*

Innovative technologies have the potential to recover high temperature waste heat with higher performances, but require the development of turbomachinery, heat exchangers and other bottoming cycle components. Based on the results and experience from previous development programs, further product development activities will be carried out to bring the technology to at least TRL 7, with a special focus on scaling and cost-effectiveness.

Activity 1.3 – Waste and Renewable Heat to Cold Generation

To reduce the environmental impact and make the industrial sector more competitive, several actions aim at increasing the efficiency of the cooling systems and reducing costs, increasing the harnessing of available waste heat, and coupling the cooling systems with renewable heat and electricity sources.

The activity would progress the TRL from 4 up (TRL progression and required budget provided in Annex 1).

Activity 1.4 - Polygeneration (heat, cold, electrical power) and hybrid plants

a. *Hybrid plants integrating waste heat recovery and renewable energy into industrial plants and processes.*
   A hybrid plant should be developed, integrating a mix of recovered waste heat, renewable heat and fuels into industrial plants and processes, to reduce their reliance from external energy. The technology should be demonstrated in a relevant environment increasing the TRL level from 4 to 7

b. *Advanced compact CHP plants of industry scale*
   Further development of advanced compact Combined Heat and Power (CHP) plants of industry scale for generation of electricity, steam and heat (i.e., polygeneration) for industrial application with fuel conversion ratios > 90%. Special requirements are operational and fuel flexibilities including low calorific gases. Deployment of CHP needs

also regulatory incentives, in order to integrate them in municipal heat and electricity grids. TRL is presently at 3-5 and should be raised to 5-7 ().

5.2 Systems

Four main areas of cross-cutting R&I activities have been identified as having a large potential for energy saving due to their applicability in several sectors. However, in order to avoid rebound effects and burden shifting, any specific R&I activity needs to be assessed vs. its potential to deliver net positive impacts in a full life cycle perspective. Electrification can only be implemented if indeed the upstream footprint of electricity supply is sufficiently low and the same counts for the hydrogen footprint reasoning. Likewise, in the case of the circular economy approach, it must be ensured that the footprint of the more circular processes is lower than would the use of virgin materials. The activities are summarised below:

Activity 2.1 - Industrial symbiosis between industries to valorise energy losses streams and better manage energy globally

Industrial symbiosis initiatives which involve the exchange of material and/ or energy flows between two or more production sites or sectors (or even an urban setting) can help in saving energy and materials, hence improve carbon, energy and resource efficiencies. Building real industrial symbiosis is however a complex topic, not only from the technological standpoint, but also from the operational standpoint: in order to be materially possible, safe, and cost effective for all partners, and for society as a whole, the energy and material transfer between different industrial units will require a very good coordination regarding, e.g. production cycles, management of unexpected stoppages, etc.

Actions in alignment with the EU Circular Economy Action Plan should build on a number of existing SPIRE / Processes4Planet (and also non-SPIRE) EU Research Projects and National initiatives. There are already more than 25 industrial symbiosis projects realised or ongoing at EU-level and many regional initiatives are operational at several levels of maturity. Actions should target in particular:

i. identification of an appropriate quantification methodology/business model for industry symbiosis, to enable price setting of interchanged commodities;

ii. identifying, assessing and testing possibilities of symbiosis between different industries or plants inside large industrial sites, and the development of enabling tools to these aims.

Cross-borders industrial clusters would benefit particularly from the European added-value of Action 6 and from the Thematic Smart Specialisation Plans (TSSP). A two-stage approach is recommended, with a first stage targeting TRL 4 to 6 within a timeframe of about 5 years, followed - for successful actions - by a second stage targeting scale-up, validation and demonstration (TRL 7-8, 5 years). Demo scale activities are essential for showcasing as a reference for a large number of industrial locations across the EU.

Activity 2.2 - Non-conventional energy sources in the process industry including carbon capture and use

Energy coming from renewable sources challenges the process industries, as there is a paradigm shift from the requirements on the demand side, governing the energy usage to the necessary flexibility of the production processes to adapt to the available supply. In more general terms, the challenge for the production processes is to react to highly fluctuating energy supply.

Actions may also cover research on changes/improvements in processes, equipment, and unit operations that can be driven completely or in a major part by sustainable electricity. Processes powered by non-conventional energy sources, such as microwave, plasma, photons, ultrasound and laser, may be particularly suitable in this respect but further research and upscaling work is necessary to demonstrate their potential and to be deployed on an industrial scale.

As part of the overall CO_2 emission reduction from energy use and especially from process emissions, carbon capture and use, is reaching very high interest to close the final gaps. The use is based on mineralization, conversion into fuels, chemicals, polymers, materials. Developments at the level of reducing energy input and purification efforts in combination with industrial symbiosis as well as upscaling are top priorities in regional and European projects.

A number of actions may be envisaged, addressing different TRL levels, depending on the technologies and the targeted sectors.

Activity 2.3 - Digitalisation: Further integration in process and plant management including plant/process design phase and processing plant retrofit

Significant steps toward higher energy efficiency will be driven by digital technologies and process automation, providing new ways to improve flexibility in plants, optimise consumption and reduce GHG emissions. A strong alignment and integration with the national strategies of Member States will be needed.

Enriched process understanding and evaluation of the impact of each decision from early process/plant design phase to production management is essential. In particular, bringing appropriate sustainability assessment at lower TRLs (starting ~TRL 4) of the process/product development where it can make a larger impact, would be very beneficial. A major breakthrough would be the availability of a software platform(s) for sustainable digital engineering, with simulation capabilities along the whole life-cycle of a plant specifically in early design phases of processes and plants. Such a platform integrating sustainability assessment along the whole life- cycle of a plant, would support optimal product and process design, plant engineering, procurement, plant construction, commissioning, possible operation modifications, as well as plant flexibility, extensions and reuse for next generation and new products. Such platform(s) could be the target of specific action and could be built on recently closed projects such as SAMT and STYLE. Several topics related to digitalisation and industry 4.0[25] should need to be considered: digital twins, advanced control systems, cloud computing, blockchain technologies applied to industry, industrial IoT, development of soft sensors, novel simulation tools, etc.

The development of cognitive equipment and plants retrieving information from sensors for continuous and batch-processes (on-line monitoring and big data analytics) are key to optimising production operations. Advanced data analytics would allow companies to convert various types of data (from R&I, engineering, production, asset management, marketing, sales, other production site, etc.) into knowledge in real-time, and effectively contribute to more sustainable manufacturing processes with more resource and energy efficiency on production sites and potentially between industrial sites.

Applicable to all Activities 2.1, 2.2 and 2.3:

A number of actions targeting TRL 4 to 8 could be considered, within a timeframe of 5 years. Activities under these three areas are expected to start at TRL 4-5 and to reach TRL 8 within 5 to 10 years. Concrete projects, financing sources, and partnerships are not defined at this stage. The target is: industrial demonstration achieved in at least 10 projects, in at least 5 industrial sectors. To date, several projects developed digital supporting systems that will become integrated in demonstration plants in the different sectors.

Some aspects of these areas are also addressed under the Horizon 2020 SPIRE cPPP work programme 2018-20, as the result of cooperation between Action 6 and the Horizon 2020 Industrial Leadership's NMPB programme, which can already be considered as an achievement of the SET Plan Action 6 Working Group. Therefore, additional actions to be proposed, should be complementary to those undertaken under SPIRE and Processes4Planet.

The development of prediction tools for the demand side, combined with matching and optimising algorithms, as a tool for intelligent support for decision processes, together with the establishment of platforms for data collection and processing, would support the balancing of energy flows in industrial plants and the collaborative management of energy intensive plants in an industrial symbiosis concept.

Activity 2.4 - Improving exchange of technological, economic, behavioural and social knowledge; training, capacity building and dissemination

This activity aims at increasing cooperation between academia, industry, authorities, research institutions, communities and SMEs in order to adopt an industrial symbiosis approach opened also

[25] The fourth industrial revolution, reflecting the move to digital transformation /automation of manufacturing/ production and related industries and value chains.

outside industrial plant perimeters (e.g. buildings, district heating/cooling networks, etc.), along the following three strands:

a) Mapping the methodological approaches and tools (covering diagnosis, evaluation and optimisation of energy efficiency of systems and processes) available in academia, research organisations, as well as best practices and business models experienced in pilot plants from industry. The objectives are: to reinforce technology networks in order to utilise resources and transform them to useful products and energy services; to contribute to the development of innovative business models along the value chain; and to disseminate these tools/models and so facilitate the implementation of energy and resource optimisation and industrial symbiosis. In former projects a strong digital basis for industrial symbiosis was made especially at the level of resource use and efficiency. Now from 2022 via the ECoP (European Community of Practice) for industrial Symbiosis the exchange, use and implementation will deployed Europe-wide.

b) Training of the workforce in cross-sectorial approaches to new energy efficiency. This includes training to industry on how to best use methodological approaches and tools and providing training and capacity building programmes to industry staff at all levels.

c) Improve the level of awareness and overall 'sustainable energy management culture' of industrial companies and SMEs. This includes: providing exchange of knowledge between universities, research organisations and industry. The role SMEs can play as intermediates, facilitators, convertors, logistic suppliers etc. needs to be determined in order to support strongly the symbiosis and to provide the missing link at the level of logistics, flow adaptation and conversion and quality of waste and energy flows.

TRLs start at 5, and finish at 7, apart from training and capacity building activities which reach a TRL of 9.

5.3 Cement

The cement sector in the European Union produces 180 million tonnes of cement a year which represents around 4.4% of global cement production[26]. It is also responsible for 2.43% of the GHG emissions (excl LULUCF) in the EU. The heart of the cement manufacturing process is the rotary kiln, where raw materials are heated up and decarbonisation of the limestone takes place through a chemical reaction referred to as calcination. It is this chemical process which causes 60%-65% of cement manufacturing emissions (process emissions). Innovation efforts in the cement industry are geared towards reducing these process emissions. The remaining emissions are combustion emissions and come from the fuels used to heat the kiln.

As set out in the European Cement Association's (CEMBUREAU) 2050 Roadmap,[27] the cement industry's aim is to become carbon neutral along the cement and concrete value chain by 2050. In order to achieve these goals, the Roadmap identifies how carbon emissions reduction can be achieved at each step of the "5 C" of cement and concrete value chair: **c**linker-**c**ement-**c**oncrete-**c**onstruction-**c**arbonation. Innovation in the cement industry will be a key driver for its low carbon transition.

In addition to projects at research stage, many other projects are at a higher TRL levels (7-9) and will now need to be scaled up and will require support from governments at both EU and national level, not only financially but also policy-wise. Innovation in the cement industry takes place in four main areas:

Activity 3.1 - Resource efficiency

a. Alternative fuels and biomass waste

The cement industry currently replaces 48% of the fossil fuels used to heat the kilns with alternative fuels sources from a variety of waste streams, including biomass waste. The industry therewith avoids 18 million tonnes of CO_2 emissions and saves 8 million tonnes of primary fossil fuels. There is no technical impediment to increase the uptake of alternative fuels and the cement industry aims to increase alternative fuel use to 60% (of which 30% is biomass waste) by 2030 and 95% (of which 50% is biomass waste) by 2050. However, most barriers to achieve these levels are regulatory in nature (lack of landfill

[26] https://cembureau.eu/about-our-industry/key-facts-figures/
[27] https://cembureau.eu/media/w0lbouva/cembureau-2050-roadmap_executive-summary_final-version_web.pdf

ban, taxation, permitting issues). In addition, maintaining access to waste streams, including to biomass waste, which is also in demand by other sectors, will be essential.

b. Alternative raw materials, clinker substitution, concrete recycling

As the largest source of CO_2 comes from the process emissions (i.e. from calcining the raw materials in the kiln), innovation and research should focus on:

- Studies to determine potential sources of alternative waste raw materials, including how waste materials and by-products from other industries can be used to replace some of the limestone, in an industrial symbiosis approach;
- Research into new types of cement clinkers with less limestone in the formulation (sulpho-aluminate clinker, ferro-aluminate clinker, belite ye-elimite-Ferrite Clinker, amorphous clinker). As these cements have different properties from conventional Portland cement clinker, they can only be used for specific applications and, once developed, their market share is estimated around 5% and this will remain a niche market;
- Research into reducing the clinker content in cement which comprises research into non-traditional substitutes such as calcined clay, silica, pozzolan materials from waste streams and slag from other industries.

Activity 3.2 - Energy efficiency

Cement kilns are already efficient, typically operating at 70%-80% efficiency. Further improvements can be made through three key routes:

- Recovering heat from the cooler to generate up to 20% of electricity needs for the cement plant;
- Early research is ongoing to use electrical heating, plasma or solar energy to calcine the raw materials which could in the future result in saving 55% of the fuel CO_2, if renewable electricity is used. The research includes an assessment of changes in the kiln design and operation;
- Ongoing research looks at a mix of biomass and hydrogen for the kiln combustion system. The mixture of hydrogen and biomass mitigates the risk that hydrogen's high heat flame in a burner alone, might not make it suitable for clinker production.

Activity 3.3 - Carbon Capture Storage and Usage (CCS/CCU)

a. Capture technologies

The cement industry has focused on a variety of CO_2 capture technologies with research undertaken at pilot scale to optimise reagent and membrane capture technologies. Trials are underway to find ways of concentrating the CO_2 in the gas stream, to make carbon capture more efficient and cost-effective. Four European cement producers have further established a research cooperation under the name "Cement Innovation for Climate (CI4C)" to investigate the practical applicability of the Oxyfuel Carbon Capture technology in the cement production process. The oxyfuel technology (from oxygen and fuel) is a clinker burning technology where pure oxygen is introduced into the kiln system instead of ambient air to assure proper combustion of all primary and secondary fuels for heat generation. In this way, exhaust gas with very high purity of CO_2 is produced in the kiln, which considerably improves the CO_2 capture potential.

b. Storage.

Captured CO_2 can be stored in geological formations where it is permanently stored (e.g. empty gas fields). It is crucial for a successful deployment of these technologies that pipelines and storage sites are identified and built and this requires a joint effort of the European Commission, Member States and industry. Of further importance is the need to address social acceptance issues related to storage, especially on-shore.

Other permanent CO_2 capture techniques include the use of recycled concrete aggregates and minerals (such as olivine and basalt). Algae can also be used to absorb CO_2 and grow biomass, which can later be used to fuel the kiln.

c. CO_2 *conversion to products.*

Projects are underway in the cement industry whereby captured CO_2 is used to create new products such as carbon neutral aviation fuel.

Activity 3.4 - Recarbonation and mineralisation

After the concrete has been produced, the calcination reaction naturally reverses. The concrete starts to reabsorb carbon dioxide from the atmosphere, mineralizing the concrete and enhancing its stone-like properties. This process, called recarbonation, occurs in all concrete structures - buildings, pavements, tunnels, dams, bridges - throughout their life. Mortar, which is made by mixing sand with cement and water, also recarbonates. It is a process that occurs naturally in all concrete structures, permanently trapping the CO_2. Thanks to recarbonation, cities effectively act as carbon sinks. A recent international review has shown that, as a first approximation, around 23% of the annual calcination emissions from cement consumed in a year is reabsorbed through recarbonation.

Research is ongoing to accelerate and enhance the recarbonation of recycled concrete. Carbon dioxide can be used to cure fresh concrete and to accelerate the recarbonation of crushed demolition concrete to create improved recycled aggregates. The technologies could be an effective means of utilising and permanently storing the carbon dioxide captured from cement manufacturing. After demolition of a concrete building, the recycled concrete aggregates have a higher surface area and can absorb CO_2 more easily within the concrete paste from the ambient air. Initial research has shown this can be accelerated by using the exhaust gases from a cement kiln, which have a higher CO_2 content, and a higher temperature, increasing the CO_2 captured by up to 50% of process CO_2 emissions.

Natural minerals such as olive or basalt when crushed can also be re-carbonated when exposed to air or kiln exhaust gases. Once carbonated these materials can be used as clinker substitutes. An important research project in this context is FastCarb.[28]

5.4 Chemicals

The chemical sector is a major contributor to building a sustainable future for Europe. The European chemical industry provides employment to over 1.1 million people in Europe and acts as a solution provider to almost all value chains including energy, transport, health, food, hygiene and construction.

The EU chemical industry, including pharmaceuticals, emitted a total of 135 million tonnes of CO_2 equivalent in 2017, down from a total of 325 million tonnes in 1990. This decrease - enabled mainly through energy efficiency, shift to less carbon intensive energy sources, and a reduction of non-CO_2 GHG emissions such as N_2O and HFCs – while production expanded by 84% over the same period.

To reach ambitious targets regarding climate change mitigation and circular economy, disruptive process technologies must be developed in addition to process efficiency options for existing technologies. Hence a portfolio of advanced process technologies and how they will work in combination, need to be developed, supported by advanced materials innovation and the implementation of enabling digital technologies.

R&I activities specific to the chemical sector under the SET Plan Action 6[29] therefore aim at:

- the integration of climate neutral energy;
- a better utilisation of alternative carbon sources such as biomass (including biogenic waste streams), CO_2 (and CO captured from industrial effluents) and waste including plastics waste; and the integrated production of low CO_2 emissions hydrogen;
- improved process efficiency through process intensification (incl. catalyst) and efficient separation technologies.

The preliminary list of areas for key R&I activities in the chemical sector has been structured as introduced below.

[28] https://fastcarb.fr/en/home/
[29] CCS activities for the Chemicals sector have not been included within Action 6

Activity 4.1 - Electrification

Energy supply in the chemical industry is currently mostly based on fossil resources. Access to cost competitive climate-neutral electricity is an opportunity for the chemical industry to reduce its carbon footprint. Electricity can be introduced directly or indirectly in chemical processes.

- Indirect use of electricity can be considered for heat[30] and steam generation or upgrade:
  - Electric heating at high temperature (e.g. e-cracker)
  - Electric heating at low temperature
  - Electricity based steam generation
  - Mechanical vapor recompression to upgrade residual steam.
- Direct utilisation of electricity via electrochemistry and use of unconventional energy forms

Novel electrochemical processes can enable new reactivities that enable molecular transformations difficult to realise via thermochemical methods. Novel process technologies for electrochemical processes can provide new production routes for various chemicals, including through the valorisation of alternative feedstock, including CO_2.

Further utilisation of electrochemical processes for the production of chemicals would require the development of new catalysts, electrodes and compact electrolysis cells.

Alternative energy forms such as ultrasound, microwave, plasma, light are non-conventional, non-contact energy sources that create the possibility for new and flexible process windows in flow reactors. Energy sourced from non-conventional energy forms is efficient in terms of being applied exactly where it is needed, as well as reducing reactions times.

Activity 4.2 - Integrated production of low CO_2 emissions hydrogen

Hydrogen is an essential element of most chemicals. Therefore, the chemical industry is both a major producer and consumer of hydrogen. Currently hydrogen is almost exclusively produced by Steam Methane Reforming (SMR) in the chemical industry, but it also occurs as a by-product in steam cracking, propane de-hydrogenation (PDH), chlor-alkali electrolysis.

As the production of hydrogen with a low environmental footprint at competitive cost is key to reduce emissions in the chemical sector, in addition to water electrolysis, technologies such as methane pyrolysis or photo-electrocatalysis are under development for cost competitive production of hydrogen.

Methane pyrolysis results in the production of hydrogen and solid carbon with less electricity requirement compared to water electrolysis technologies. The utilisation of climate neutral electricity can enable the production of low CO_2 emissions hydrogen at industrial scale from various sources of methane including biomethane or methane by-product from e-crackers.

Photo-electrocatalysis (PEC) can enable the production of H_2 from water without external electricity input. PEC cells operate at ambient pressure and temperature and at lower potentials than electrolysis which makes PEC more energy efficient.

Activity 4.3 - Utilisation of plastic waste as alternative feedstock in the chemical industry

Innovative process technologies can enable the utilisation of waste, in particular plastic waste for the production of chemicals and polymers in the chemical industry. To meet the ambitious European objectives, much more waste plastic needs to be recycled and a broader range of markets need to be served with plastic products containing recycled content. Chemical recycling technologies break down plastics and transform them into valuable secondary raw materials to produce new chemicals and plastics with the same quality as those made from fossil resources. Chemical recycling complements existing mechanical recycling to recycle mixed or contaminated plastic waste that otherwise would be incinerated or sent to landfill.

[30] Heat pumps are addressed in the section Heat/cold recovery

Different types of chemical processes can be used to recycle plastic waste:

- Pyrolysis and gasification for conversion of mixed plastic waste to (oil or gas) feedstock. The conversion takes place in a reactor in absence of oxygen (pyrolysis) or presence of oxygen (gasification). In a following step, potential contaminants are isolated and removed. The produced oil or gaseous feedstock (re)enters the chemical production chain at the refinery or cracker level as secondary raw material replacing newly extracted fossil feedstock.
- Depolymerisation process – often referred to as chemolysis or solvolysis – uses different combinations of chemistry, solvents and heat to break down sorted polymers into monomers.
- Dissolution: sorted plastic waste is dissolved to extract the polymer.

Activity 4.4 - Utilisation of CO_2 / CO as alternative feedstock in the chemical industry

The utilisation of CO_2 (and CO from 'industrial waste gases') as alternative feedstock is one of the options that can be considered by the chemical industry to reduce the environmental footprint of chemicals and polymers.

A broad portfolio of technologies can be used and needs to be further developed to use CO_2 as feedstock including:

- Power-to-X technologies in particular for the production of syngas, methanol.
- Direct electrocatalysis to C_1 and C_{n+1} molecules
- Biotechnology routes to C_1 and C_{n+1} molecules
- Direct utilisation of CO_2 for the production of C_{n+1} molecules through thermocatalytic routes
- Direct utilisation of CO_2 for the production of polymers through thermocatalytic routes
- Direct utilisation of sunlight through photo(electro)catalytic systems.

In addition, technologies for efficient capture and purification of CO_2 from various sources (see also efficient separation technologies – see Activity 2.6) are essential to improve energy efficiency and cost.

Activity 4.5 - Utilisation of Biomass as feedstock for chemicals and materials

Resources of biological origin offer the chemical industry an opportunity to diversify its feedstocks to produce chemicals and polymers. The chemical industry intends to increase the production products from sustainably sourced biomass, further increasing the resource efficiency and diversity of supply. The chemical industry is seeking to scale-up bio-based products of novel or analogue chemical structure, with an equal or improved performance and functionality compared to existing alternatives, mostly fossil derived, as well as an improved sustainability profile.

Development of technologies is needed across all processing stages of biomass transformation into bio-based products (this includes the pre-treatment stage, conversion stage, downstream and the processing stage). Technologies will be based on mechanical, (thermo)chemical and (electro)catalysis processes, industrial biotechnology and biocatalysis processes.

Activity 4.6 - Process efficiency including separation technologies

<u>Process intensification,</u> including reactor design concepts and equipment and new catalyst development can provide major opportunities for resource and energy efficiency as chemical reactions can be achieved at optimal conditions with significantly less side reactions creating fewer by-products, and using fewer auxiliary materials.

The introduction and further penetration of process intensification technologies can also achieve faster and more flexible modular and standardised chemical production including multipurpose plants.

<u>Separation technologies</u> are of crucial importance for large-scale chemical and biotech processes, as they are essential in chemical processes for the purification of the products, recycling of solvents or catalysts, further valorisation of by-products or gaseous effluents, removal of harmful substances etc. as well as access/pretreatment of alternative feedstock such as biomass and CO_2.

Most mature separation technologies are energy intensive, and separation operations can represent up to 50% of energy consumption in chemical plants. Therefore, intensified separation technologies and their control technologies have to complement higher selectivity of the reactions.

Advanced separations and further innovation in this area – including for retrofitting - are required to significantly reduce energy consumption and costs.

Advanced tools to support decision making from design phase to production (see cross-sectorial priority Systems 6.3 Digitalisation) will also be key enabling priorities for the chemical sector.

Process efficiency can be complemented at plant and site level with the implementation of other optimisation measures such as energy recovery technologies, including from low temperature energy streams which still require R&I activities to increase their performance and reduce their cost.

5.5 Iron & Steel

There are presently two main routes for producing steel depending on the raw material:

- The primary route which converts iron ores into steel through the use of chemical agents (reductants) mainly from coke or coal in blast furnaces – this route is traditionally called blast furnace- basic oxygen furnace route (BF-BOF route) or integrated route.
- The secondary route which consists in melting iron-bearing material, in particular scrap steel, using electricity in an electric arc furnace (EAF).

Both production routes recycle scrap steel and are complementary. They are based on processes that are already well optimised thermodynamically, so that further efficiency improvements are very limited. Therefore, breakthrough technologies are required.

The ambition of the iron and steel sector is to reduce its total CO_2 emissions from EU steel by 30% by 2030 compared to 2018, and 80-95% by 2050 compared to 1990, ultimately leading to climate neutrality. This will contribute to the EU efforts towards a climate neutral continent. At the same time, the competitiveness and the viability of the EU steel industry – both for the primary and the secondary routes and including the wider steel value chain should be preserved, making sure also that EU production will be able to meet the growing EU demand for steel products.

Considering the above ambition, there are two main technological pathways in the steel sector with the aim of increasing energy efficiency, but also of reducing CO_2 emissions and maintaining competitiveness in the frame of ETS reform that will reduce the amount of free CO_2 emission allowances in the future.[31] These pathways are:

- **Carbon Direct Avoidance (CDA),** to avoid emitting carbon during steelmaking –through the use of hydrogen or electricity to replace fossil carbon.
- **Smart Carbon Usage (SCU),** consisting in ways to use less fossil carbon in steel production (process integration) and ways to avoid emitting carbon to the atmosphere (Carbon Capture, Utilisation, and Storage - CCUS)

Furthermore, there are overarching **circular economy** approaches, including: the enhanced recycling of steel, the enhanced utilisation of by-products, and the further improvement of resource and energy efficiency. Each of these pathways includes groups of technological approaches.

It should be noted that some technological solutions may entail **combinations of the above technological pathways**. The reliable availability and abundant supply of low-or CO_2-neutral energy (mainly electricity and hydrogen) at economically viable, affordable cost levels is a necessary pre-condition for the successful transformation of the steel sector in the coming decade and beyond.

Figure 5-1 identifies both the main pathways to be pursued and a sample of some of the proposed or ongoing projects in each pathway.

[31] https://www.eurofer.eu/publications/reports-or-studies/low-carbon-roadmap-pathways-to-a-co2-neutral-european-steel-industry/

Figure 5-1 The EU steel industry's strategic technological pathways

Pathways/ Groups	**Circular Economy** **Enhancing the recycling of steel (e.g. scrap in BOF/EAF*) and its by-products, Resource efficiency** *BOF= Basic Oxygen Furnace EAF= Electric Arc Furnace			
	Smart Carbon Usage (SCU)		**Carbon Direct Avoidance (CDA)**	
	Process Integration with reduced use of carbon (+CCS)	**Carbon Valorisation/ Carbon Capture and Usage (CCU) (+CCS)**	**Hydrogen**	**Electricity**
Description	**Integration of process steps and internal use of process gases**	**Using CO/CO_2 from steel mill as raw material (Biological and chemical conversion of CO/CO_2)**	**Use of renewable electricity in basic steelmaking, e.g. production of H_2 to replace carbon**	
Projects/ Initiatives	HISARNA, TGR-BF-Plasma (IGAR), PEM, STEPWISE, Torero	Steelanol, Carbon2Chem, FReSMe, Everest, Carbon2Value	HYBRIT, H2Steel (H2Future, SuSteel, Hybrid Steel Making), tkH_2Steel, GrInHy, SALCOS, Hydrogen Hamburg, SIDERWIN	

The proposed activities of the EU steel sector in the SET Plan Action 6 will focus on the technological approaches of the above technological pathways:

Activity 5.1 - CO_2 emission avoidance through direct reduction of iron ore using hydrogen

CO_2 emissions can be avoided by replacing fossil carbon (e.g. from coal and coke) by hydrogen to reduce the iron ore (meaning to remove oxygen from the iron ores). The hydrogen would be produced by electrolysis, allowing the use of electricity from renewable sources.

Fiche 1.1 describes ongoing projects that contribute to the hydrogen reduction, including hydrogen plasma-based Iron ore reduction (SUSTEEL), electrolyser projects (H_2Future, GrInHy) and feasibility studies (HYBRIT-PFS and MACOR) for future projects of full-scale integration of hydrogen reduction in steel plants.

Altogether, these ongoing and future projects have a potential for cooperation between several projects in several Countries, to tackle the environmental, regulatory, economic and social challenges of the steel industry at European level. The full-scale demonstration (~€1-2 billion/project) will require a financing mix, possibly including private/public equity/loans/grants, specific to these first-of-a- kind demonstrations.

Activity 5.2 - CO_2 emission avoidance through direct reduction of iron ore using electricity

CO_2 emissions can be avoided by replacing fossil carbon (e.g. from coal and coke) by electricity to reduce the iron ore. The hydrogen would be produced by electrolysis, allowing the use of electricity from renewable sources.

Activity 5.3 - Process integration: HIsarna smelting reduction process for lowering energy consumption and CO_2 emissions of steel production

HIsarna is a Smelting Reduction process concept, in which the main savings come from handling raw materials directly without the need for agglomeration or coking. This concept incorporates a cyclone for heating and melting iron ore and a bath smelter. It is being tested with higher steel scrap additions and biomass that results in lower specific energy consumption and lower CO_2 emissions.[32] It is also designed

[32] Project Development of a Low CO2 Iron and Steelmaking Integrated Process Route for a Sustainable European Steel Industry, Programme SILCII, Grant agreement ID: 654013

to produce CO_2-rich off-gas, by using pure oxygen rather than enriched air, making end-of-pipe carbon capture easier.

As a continuation of ongoing EU and national projects, the proposed R&I Activity will on the one hand further progress the pilot-plant research following completion of this fifth campaign and, on the other hand, focus on design, impact and financial aspects of a scaled-up demonstration plant. The Activity is an essential step in the development chain to bring the technology toward TRL>=8.

Activity 5.4 - Process integration: Top Gas Recycling – Blast Furnace (TGR-BF) using plasma torch

This TGR-BF technique will recover all CO + H_2 in the top gas of the blast furnace, for re-injection in the furnace. This will increase the carbon-efficiency in the furnace by 80%, reduce specific energy consumption and CO_2 emissions.

The TGR-BF project consists of several phases including the design of a plasma torch for steel mill gas conversion, the design of a novel tuyere allowing to inject coal, oxygen and steel mill gas into the blast furnace, the engineering and construction of all this equipment on one European blast furnace.

Activity 5.5 - Carbon Capture Usage and Storage

The capture and conversion of CO and CO_2 (without or in combination with H_2) may allow using carbon from steel mill exhaust gases as feedstock (carbon source) for new products (fuels and chemicals). Hence the carbon is used a second time as resource rather than being emitted. The conversion can be biological transformation by algae into new organic compounds or chemical transformation into chemical building blocks for the chemical industry or synthetic fuels for the transport sector. It can also be mineralisation, e.g. for making building materials. Notably two processes based on chemical transformation are of particular interest in the steel sector: the ethanol fermentation project STEELANOL that is being developed in Belgium and the cross industrial project Carbon2Chem located in Germany.

Activity 5.6 - Circular economy

Enhanced recycling of steel (such as ferrous scrap), enhanced utilisation of steel by-products (such as slags) and residues (such as dusts) as well as increased recovery of waste heat to increase resource and energy efficiencies in both primary and secondary steel production routes. The main bottleneck is the refining capacity to remove tramp elements for high quality products.

5.6 Pulp & Paper

The production of paper generally consists of two processing parts: the isolation of cellulose fibres from wood and other lignocellulosic feedstock (pulping) and the production of paper and board from cellulose fibres (paper making).

The pulping processes currently applied are very effective and CO_2 neutral. They isolate high-quality cellulose fibres, while the remaining lignin serves as a sustainable energy source feeding the process. Pulping chemicals are being recovered. However, the increasing demand for bio-based feedstock to replace fossil carbon in chemicals and materials, calls for a pulping process with lower energy demand. This allows the lignin side stream to be used as a feedstock for new materials while keeping a CO_2-neutral process.

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

The pulp and paper sector is the biggest producer of green electricity, renewable heat and biofuels in Europe. 60% of their energy consumption is biobased.[33] Emerging energy conversion technologies and fuel mix change offer great potential to further strengthen this position. The combination of onsite bioenergy production with carbon capture and storage (BECCS) provides the pulp and paper sector with the opportunity to achieve negative emissions. The challenge is to make this technology cost-efficient. In

[33] Figures from Key Statistics. European Pulp & Paper Industry (2020) Cepi https://www.cepi.org/wp-content/uploads/2020/07/Final-Key-Statistics-2019.pdf

addition to initiatives to decarbonise heat, innovation in this sector is focused on the development of breakthrough processes for pulping and papermaking with significantly lower energy demand.

The pulp and paper sector aims to increase their product portfolio and create new markets for renewable, low-carbon products. This boosts the competitiveness of several industrial sectors through significantly improving their environmental performance. The product portfolio includes new functional cellulose-based applications and high value products from residual and side streams (e.g. lignin, hemicellulose and terpenes). The pulp and paper sector works together with other sectors, like the chemical industry and also the machine suppliers, to implement innovative and efficient technologies and to develop new products along with more productive, greener processes.

Activity 6.1 - Integral drying and heat recovery processes

Innovative heat recovery technologies, like mechanical vapour recompression and other kinds of heat pumps, may realise a significant reduction of energy required for steam production. However, effective use of these techniques inherently requires a starting vapour at high temperature and low air content. Though drying technologies in papermaking processes are highly efficient in achieving almost 100% energy transfer for water evaporation, the processes are not designed for resulting in a vapour of which heat can efficiently be recovered. Projects are focused on the development of innovative drying technologies that allow efficient heat recovery (e.g. superheated steam drying, air/vapour separation).

Activity 6.2 - Papermaking without water evaporation

Papermaking without water would mean a complete plant redesign. Strength and stiffness of paper comes from hydrogen bonds between the cellulose fibres. Effectively breaking and forming these bonds by addition and removal of water has been the core of papermaking processes since its invention more than two millennia ago. However, the removal of water requires large amounts of energy in current papermaking processes. This could either be solved by technologies that can isolate water from a wet paper web without evaporation (e.g. electric field, electro-osmosis) or by totally eliminating water from the papermaking process. In both cases, the challenge is how to induce hydrogen-bonded paper without the presence and evaporation of large amounts of water.

Activity 6.3 - Process optimisation and electrification (modular approach)

Unit process optimisation and intensification can lead to energy savings in several parts of the process. This includes mild repulping technologies, more effective fibre refining technologies and innovative mechanical dewatering technologies so that less thermal drying is needed. Electricity-based technologies in dewatering and drying (e.g. microwave and ultrasound) may also lead to increased energy efficiency.

Activities under those four areas vary between TRL 2 (without water) to TRL 8 (electrification) thus covering both long-term research and short-term application-driven demonstration projects.

Activity 6.4 - Mild pulping processes

Research on efficient wood fractionation processes has grown exponentially in the past decade. The challenge is to realise energy-efficient integral fractionation processes that isolate and convert all wood components into high-value applications. The innovative Deep Eutectic Solvents have proven to allow pulping at much milder processing conditions, though achieving cellulose fibres at sufficient quality for papermaking is still a challenge. EU and national projects are ongoing. On the one hand, the proposed R&I activities will be further progressing the research on pilot and demo scale. On the other hand, fundamental research to tailor the natural cooking liquids and recovery processes to achieve higher quality products at higher efficiency.

Activity 6.5 - Onsite renewable energy production

Pulp mills are already CO_2 neutral through the effective integrated incineration of lignin-containing 'black liquor' in recovery boilers. Also, other by-products from forest-based industries, such as saw-dust, bark and tall oil, are relevant sources for onsite production and use of renewable energy and fuels. Emerging technologies, like gasification, torrefaction, carbonisation and pyrolysis can improve energy efficiency and also offer wider opportunities for the valorisation of the side streams and thus increase resource efficiency.

Another renewable energy source is biogas from anaerobic wastewater treatment plants from onsite digestion of biogenic waste streams from paper mills or in collaboration with regional biogas initiatives. Biogas can be fed into the existing highly efficient (>95%) CHP operations of paper mills. In addition, the energy use of a recycled paper mill can be further decarbonised by using reject streams for incineration, gasification or liquifying.

Innovations in concentrated solar thermal also offer opportunities to replace part of the fossil-based heat with renewable heat.

In all TRL development phases, the projects should be co-financed via public grants (national and/or European) and private funds. Cooperation between the paper industry and innovative technology developers and machine suppliers is crucial for success. Moreover, the further development of cross-cutting technologies improving heat recovery, system integration, digitalisation and industrial symbiosis is essential for energy saving in the pulp and paper sector and allowing successful development and implementation of technological innovations.

Activity 6.6 - Biomass as alternative feedstock

Shared activity, see Chemical 4.5.

6 ACTION 6 TARGETS

In each of the SET Plan Actions' Implementation Plans (IP), the Implementation Working Groups (IWGs) are required to set collectively agreed technology targets. This section therefore presents Action 6's targets and the logic behind how they were established.

In 2016, the European Commission, the Action 6 SET Plan countries and industry representatives agreed targets, as outlined in the Declaration of Intent (DoI). In 2017, the IWG elaborated these into the 2017 IP.[34] These defined activity targets based on the technology's maturity and economic viability (as defined by TRL scale). Sector specific activities had two overarching targets for 2030 (considering technologies with TRL between 4-6 and those 7 or above separately). Cross-cutting activities focused on developing and demonstrating technologies to TRL 8, by 2025.

In this revised IP, each sectorial Thematic Group (TG) presents their sector-level ambitions, which the SET Plan Action 6 R&I priorities aim at contributing to (shown in (Table 6-1). Additionally, targets corresponding to each R&I priority activity area for all TGs are presented (Table 6-2 and Table 6-3). Where relevant, additional information on the targets and activity selection, including prerequisite conditions for each to be achieved, are included in Annex 2.

[34] https://setis.ec.europa.eu/system/files/set_plan_ee_in_industry_implementation_plan.pdf

Table 6-1 Sector level targets (Sector-specific Thematic Groups only)

TG	2030	2050
Cement[35]	Reduce gross CO_2 emissions by 30% and value chain emission by 40% by 2030.	Carbon neutrality along the cement-concrete value chain by 2050.
Chemicals	Deployment between 2030 and 2050 of innovative technologies is aiming at a climate-neutral chemical industry by 2050[36] and increased carbon circularity.	
Iron & Steel	Reduce total CO2 emissions by 30% by 2030 compared to 2018 (which corresponds to a reduction of around 55% by 2030 compared to 1990.[37]	Reduce CO2 emissions stemming from EU steel production by 80-95% compared to 1990 levels by 2050, ultimately leading to climate neutrality.[38]
Pulp & Paper	-	Decarbonising by 80% to reach climate neutrality, while creating 50% more added value by 2050.

The targets corresponding to each R&I priority activity area (Table 6-2 and Table 6-3) describe realistic but ambitious aims for R&I development, demonstration projects and deployment for each activity. They consider progress over the short, medium and long term (2025, 2030 and 2040/50). Additionally, as the activities included consider Action 6's 2021 expanded focus on energy, energy efficiency, carbon emissions and feedstock, the corresponding targets also consider these areas, as appropriate. In addition to the activity targets, each Thematic Group has an overall sector target for the same time periods.

There are two important motivations for these changes. First, the changes are expected to increase the relevance and usefulness of the targets for the IWG, industry stakeholders and Countries. Second, the changes better align Action 6's work with the European Green Deal via the increase in scope beyond energy efficiency and by the consideration of progress up to 2050 (the Green deal aims to achieve 55% emissions cut by 2030 and climate neutrality by 2050).

Structuring the targets per activity and with a range of timeframes will enable the IWG to track the progress of each research area in terms that are relevant to the specific activity. Monitoring of progress against these targets will be organised between the Thematic Group Leads and Secretariat and will draw on information in relevant documents, such as association's roadmaps, in these areas.

There is variation in the format and focus of the targets between the different TGs. Thematic Group Leads each drew on existing research and literature to develop their targets and ensure they are aligned with other industry initiatives working towards the Green Deal's 2050 target. This means, for example, that some focus on R&I progress as measured by key milestones along the technology's journey up the TRL scale (e.g. Pulp & Paper), whereas others focus on impacts in terms of reduction in CO_2 emissions or energy use (e.g. cement). This variation reflects the diverse nature of the sectors and industrial processes covered by Action 6. In some cases, priority areas cover a range of different technologies resulting in wide ranging emission reduction targets particularly by 2050.

The basis and quantification of targets for the sectors are addressed in Annex 1. When presented, the primary energy savings potential and GHG emissions reductions potential are calculated on the assumption that the developed/demonstrated technologies are fully deployed across the EU27+UK.

[35] In its Carbon Neutrality Roadmap "Cementing the European Green Deal", published in May 2020, CEMBUREAU, https://cembureau.eu/media/w0lbouva/cembureau-2050-roadmap_executive-summary_final-version_web.pdf
[36] As currently studied in the context of the Cefic Transition Monitoring project due to be published late 2021
[37] https://www.estep.eu/assets/Uploads/ec-rtd-he-partnerships-for-clean-steel-low-carbon-steelmaking.pdf
[38] The Iron & Steel targets are adapted from the Clean Steel Partnership's Objectives and KPIs from the roadmap: https://www.estep.eu/assets/Uploads/200715-CSP-Roadmap-version-public-consultation.pdf.

Table 6-2 Cross-Cutting TG Targets

<table>
<tr><th colspan="4">Heating & cooling</th></tr>
<tr><th>Activity</th><th>2025</th><th>2030</th><th>2050</th></tr>
<tr><td>1.1 Heat or cool upgrade from low to high grade</td><td>Develop and demonstrate (to TRL 7 for temperature up to 200/250°C and to TRL 6 for temperature above 250°C) solutions enabling small and large industries to cost effectively reduce their energy consumption by 5% by cost effectively upgrading excess heat for more valuable application elsewhere in the process.</td><td rowspan="5">Increase efficiency by 5% compared to 2025 level;

Reduce LCOE by 10% compared to 2025 level.

Develop and demonstrate to (TRL 8) hybrid systems (considering e.g. heat storage, high temperature heat pumps, etc.)</td><td rowspan="5">Carbon neutral manufacturing process:

Reduce use of Critical Raw Material;

Reduce emissions at production level;

Extending components operating lifetime + 25%; Increase the re-use of end of life material.</td></tr>
<tr><td>1.2a Waste heat to power</td><td>Develop and demonstrate (to TRL 7) solutions enabling small and large, industries to cost effectively (€/kW) recover 10% of low temperature waste heat (100-300˚C) while striving to reduce GHG emissions proportionally (tons CO_2 avoided).</td></tr>
<tr><td>1.2b High temperature waste heat recovery to generate electrical power</td><td>Develop and demonstrate (to TRL 7) solutions enabling small and large, industries to cost effectively (€/kW) recover 20% of high temperature waste heat (>300˚C) while striving to reduce GHG emissions proportionally (tons CO_2 avoided).</td></tr>
<tr><td>1.3 Waste and renewable heat to cold generation</td><td>Develop and demonstrate (to TRL 7) cost effective cooling solutions using recovered and/or renewable heat .</td></tr>
<tr><td>1.4 Polygeneration (heat, cold, electrical power) and hybrid plants</td><td>Develop and demonstrate (to TRL 7) cost effective polygeneration solutions and integration of renewable and recovered waste heat in the industrial processes.</td></tr>
</table>

Systems			
Activity	**2025**	**2030**	**2050**
2.1 Industrial (urban) symbiosis	Develop and demonstrate solutions, including the needed local logistics, enabling small and large industries to reduce their common energy consumption by 10 to 20% while striving to reduce GHG emissions proportionally.		
	-	~15 industrial symbiosis full scale hubs.	> 200 industrial symbiosis full scale hubs.
2.2 Non-conventional energy sources, including CCU	Develop and demonstrate solutions enabling small and large industries to reduce their energy consumption by 20% while striving to reduce GHG emissions proportionally.		
	-	Optimal use of energy from biomass residues and waste residues reaching 20% share in the energy resources. Availability of digital systems to manage energy mix applications in heating and cooling of energy intensive processes. More than 20% less energy use in capture and purification of CO_2.	-
2.3 Digitalisation	Implementation of process control and process automation solutions in 10% of plants.	Implementation of process control and process automation solutions in 20% of plants.	Implementation of process control and process automation solutions in 100% of plants.
2.4 Knowledge exchange, training and capacity-building	Mapping of training and skills needs and setting up of curricula (based on knowledge exchange).	New curricula at university/high schools (capacity building) on innovative skills and education in agreement with the SET-plan technological, advocacy and management needs. Tailor made training and skills development for in-company training based on the new needs (technical, advocacy, management) defined in SET-Plan.	-

Table 6-3 Sectorial TG Targets

Cement		
Activity	**2030**	**2050**
3.1 Resource efficiency		
3.1a Alternative fuels - sourced from a variety of waste streams, including biomass waste)	60% alternative fuel use of which 30% biomass waste.	90% alternative fuel use of which 50% biomass.
3.1b Alternative raw materials, clinker substitution, concrete recycling (overall target)	3.5% reduction of process CO_2 using decarbonated raw materials.	8% reduction of process CO_2 using decarbonated raw materials.
3.1b (i) New types of clinkers[39]	2% reduction in process emissions CO_2.	5% reduction in process emissions CO_2.
3.1b (ii) Reducing clinker content	Reduce ratio to 74% (from 77% in 2021)	Reduce ratio to 65%
3.1b (iii) Concrete: improved mix design, new admixtures	Reduce cement in concrete by 5%	Reduce cement in concrete by 15%
3.2 Energy efficiency	4% thermal efficiency improvement.	14% thermal efficiency improvement.
3.3 CCS/U	Pilots and demonstrators by 2030 (dependent on infrastructure and a proper accounting framework).	42% reduction in CO_2 emissions through CCS.
3.4 Recarbonation and mineralisation	-	Up to 8% saving in total CO_2 emissions for cement manufactured (assuming a 23% of process emissions of cement used being captured annually)

[39] For reference, only suitable for niche applications in 2025.

<table>
<tr><th colspan="5">Chemicals</th></tr>
<tr><th>Activity</th><th colspan="2">2030</th><th colspan="2">2050</th></tr>
<tr><th></th><th>At activity level[40]</th><th>Illustrative examples
(These are individual examples and not representative of the broader scope of the Activity)</th><th>At activity level[41]</th><th>Ambitions</th></tr>
<tr><td>4.1 Electrification</td><td rowspan="6">Demonstration projects to be launched by 2030.</td><td>First pilot project for e-cracker with the objective to reduce up to 90% of related GHG emissions.</td><td rowspan="6">Deployment of new technologies between 2030 and 2050.</td><td>Indirect and direct electrification[41] of chemical processes will be a key contributor to the abatement of GHG emissions in the chemical sector (including combustion emissions that represented 67 Mt CO_2 eq. in 2018 in EU 27)</td></tr>
<tr><td>4.2 Integrated production of Hydrogen with low carbon footprint*</td><td>First demonstration unit for the production of hydrogen with a new[42] technology enabling a reduction of at least 90% of GHG emissions vs current production of hydrogen from SMR.</td><td>Integrated production (using various technologies) of hydrogen used as feedstock without GHG emission.</td></tr>
<tr><td>4.3 Plastic waste as an alternative feedstock*</td><td>Demonstration of gasification and pyrolysis technologies with improved process yield and the ability to handle a wider range of mixed plastic streams.
Pilot units for new technologies for plastic types where currently chemical recycling process options only exist at lab scale.</td><td rowspan="3">Large-scale deployment of a combination of technologies enabling the utilisation of plastic waste, CO_2 and biomass as feedstock for the production of chemicals and polymers, as a key contributor to carbon circularity and climate neutrality.</td></tr>
<tr><td>4.4 CO_2 / CO as an alternative feedstock*</td><td>Demonstration of robust CO_2 conversion processes with high productivity enabling to improve economics of the conversion of CO_2 to C_1 molecules.
Pilot unit for new processes for direct conversion of CO_2 to C_{n+1} molecules</td></tr>
<tr><td>4.5 Biomass as an alternative feedstock*</td><td>Pilot / demonstration[43] for lignin pre-treatment and conversion enabling the production of bio-based aromatics.</td></tr>
<tr><td>4.6 Process efficiency</td><td>Pilot / demonstration[44] units for alternative (e.g. membrane, adsorption) to distillation technologies enabling a switch from thermal to electricity-driven separation</td><td>Deployment of various advanced separation technologies to contribute to GHG emissions reduction and the competitiveness of the European chemical industry.</td></tr>
</table>

[40] Each Activity dedicated to the chemical sector includes a portfolio of technologies that are currently at various TRLs.

Iron & Steel[45]		
Activity	**2030**	**2050**
5.1 CO_2 emissions avoidance through direct reduction of iron using Hydrogen	Reduction degree of iron oxide: > 90 % (KPI 2a) Replacement rate of fossil carbon by hydrogen injection: > 10 % (KPI 2b) Replacement rate of natural gas by H2 in the feed of the direct reduction plant: > 50 volume-% (KPI 2c)	Develop all relevant technologies at TRL8 to reduce CO2 emissions stemming from EU steel production by 80-95% compared to 1990 levels by 2050, ultimately leading to climate neutrality.[46]
5.2 CO2 emissions avoidance through direct reduction iron using electricity*	Electric efficiency of the electrolytic cell: > 85% (KPI 3)	
5.3 Process integration: HIsarna smelting reduction process for lowering energy consumption and CO2 emissions of steel production	Decrease the use of energy per tonne of steel for clean steel making: > 10 % specific energy consumption reduction for a dedicated process (KPI 9)	
5.4 Process integration: Top Gas Recycling – Blast Furnace (TGR-BF) using plasma torch	Demonstration of a transformative technology for the blast furnace; increase of the re-use of off-gases in the blast furnace, reducing the consumption of coal per tonne of steel produced and cutting CO2e emissions by up to 20%[47].	
5.5 Carbon Capture and Usage (CCU)*	CO2 capture rate from process/off-gases: > 95 % from dedicated gas streams (KPI 6)	
5.6 Circular economy*	Re-use and recycling of solid residues co-generated during the steel production process and reduction of their landfilling rate: internal and external recycling and re-use rate > 85 % (in total) (KPI 10) Low-quality scrap input share over the total scrap input increased by at least 50% or more compared to the usual practice for a specific steel quality (KPI 11)	

[41] Provided cost-competitive access to climate-neutral electricity
[42] Other than water electrolysis technologies powered by electricity.
[43] Pilot or demonstration unit depending on the process and/or target product.
[44] Pilot or demonstration unit depending on the process and/or target product.
[45] The Iron & Steel targets are adapted from the Clean Steel Partnership's Objectives and KPIs from the roadmap: https://www.estep.eu/assets/Uploads/200715-CSP-Roadmap-version-public-consultation.pdf. The two exceptions are activities 5.3 and 5.4 which are taken from projects working on these activities and their expected progress.
[46] The Iron & Steel targets are adapted from the Clean Steel Partnership's Objectives and KPIs from the roadmap: https://www.estep.eu/assets/Uploads/200715-CSP-Roadmap-version-public-consultation.pdf.
[47] As per the ArcellorMittal Climate Action Report 2 July 2021, available at: https://corporate-media.arcelormittal.com/media/ob3lpdom/car_2.pdf

Pulp & Paper[48]			
Activity	**2025**	**2030**	**2050**
6.1 Integral drying and heat recovery processes	Develop innovative integral drying and heat recovery solutions.	Demonstration of solutions in operational industrial environment by 2030.	Market penetration of integral drying and heat recovery system of 40% by 2050.[49]
6.2 Paper making without water evaporation.	-	Piloting and demonstration of paper making without water evaporation technology in operational industrial setting.	Successful demonstration will lead to commercial application, leading to >10 commercial scale plants in 2050.[50]
6.3 Process optimisation and electrification (modular approach)	Development and piloting of modular technologies.	Demonstration of Process optimisation and electrification in operational industrial setting by 2030.	Achieve market penetration reaching between 10% and 70% in 2050, depending on the specific modular technology.[42]
6.4 Mild pulping technologies	-	First commercial implementation by 2030.	Market penetration reaching 50% by 2050
6.5 Onsite renewable energy conversion		Demonstration and implementation of innovative technologies up to 2030.	-
4.5 / 6.6 Biomass as alternative feedstock for emerging bio-based products	Continuous development, demonstration and implementation of various new bio-based products from forest biomass. The share of emerging bio-based products (other than pulp and paper) will substantially increase as to contribute to the sector's ambition of 50% more added value in 2050. (Currently 3% of European pulp and paper industry sector turnover)		

[48] Additional information on requirements for these targets to be met can be found in Annex 1
[49] Target subject to the success of the 'competing technologies' being developed simultaneously.
[50] Further market penetration is subject to the success of the 'competing technologies' being developed simultaneously.

7 NEXT STEPS FOR ACTION 6

The successful delivery of work under Action 6 is the result of the contributions of IWG members supported by DG ENERGY through an Action 6 secretariat. Work conducted to date has aimed to address the key challenges in the deployment of activities identified in the IP. The IWG6 will continue monitoring progress of the execution of the IP going forward.

The aims of the Action 6 IWG are to:

- Maintain a dialogue between the European Commission and the SET Plan countries and stakeholders to identify and address the actions needed to progress the activities outlined in the IP;
- Provide advice to industry and the SET Plan countries with the aim of removing non-technical barriers to realising the Action 6 targets;
- Provide clarity on the funding instruments currently available at National and EU level (and identify gaps);
- Support SET Plan countries to understand where their funding programmes can contribute to Action 6 and complement Horizon Europe calls;
- Identify potential areas for collaboration between SET Plan countries and/or industry stakeholders and mobilise interested parties;
- Provide a means for continuous monitoring and communication of emerging technologies and activities along the pathway towards further decarbonisation and increased energy efficiency in order to inform SET Plan countries on the progress of these technologies.
- Participate in SET Plan's initiative for cross-collaboration between Actions;
- Explore and exploit opportunities for the implementation of R&I activities under the challenge 6 "Integrated Industrial Energy Systems" of the CETP – Clean Energy Transition Partnership of HEU;
- Identify synergies with existing and upcoming R&D initiatives at EU level including Horizon Europe Partnerships.

Finally, the IWG6 considers it important to collaborate with SETIS and the other SET Plan Working Groups where strong synergies can be developed, such as the cross thematic areas proposed by SETIS in 2021 and directly with other actions (such as Action 9 on CCU/S). Further interest in collaboration has been expressed from four other Actions.[51]

Relevant materials from all IWG will be made available on the Action 6 website https://setis.ec.europa.eu/implementing-integrated-set-plan/energy-efficiency-industry .

Next steps proposed here are subject to change based on feedback of the IWG members and SETIS.

[51] Implementing the SET Plan – 2020 Report - JRC122587 https://publications.jrc.ec.europa.eu/repository/bitstream/JRC122587/set_plan_2020_online_interactive-lw.pdf

ANNEXES

8 ANNEX 1: R&I FOCUS

This annex presents the R&I focus related to the priority activity areas identified in Section 5. It is complemented by the following annex including the fiches which describe the R&I activities in detail.

8.1 Heating and Cooling

Heat and Cold generation, upgrade and recovery technologies are in development or exist but are not yet economically viable to be deployed in all industrial processes. Their impacts depend on several factors related to the considered process. Thus, the targets related to the Heat/Cold Recovery priority are better quantified in terms of the advancement of the technology (TRL). For some of the technologies, the primary energy saving and GHG emissions reduction potentials are described in the activity fiches by considering the waste heat potential.

8.2 Systems

Systems is focusing on the integration of concepts (based on technologies), overall needed systems (such as CCU), embedding in the regional setting (including logistics) and taking into account training and education (including citizen awareness). In order to do this integration, strong digital tools are needed to manage the data flows, improve the processes and guarantee quality. All these aspects start from a sectorial/company need, but depend on local logistics and investment support, as well as local acceptance and awareness. So, local-public/private partnering is extremely important.

<u>Existing but not yet economically viable technologies</u>

Several industrial symbiosis projects do exist especially at large industrial sites (inventory will be made by the European Community of Practice)

1. About 25 Industrial-symbiosis projects are realised at EU-level with focus on flow exchange, business models, IT-support, etc.
2. Process electrification (e.g. electric furnaces, crackers)
3. Electrochemical conversion in steel, non-ferrous metals and chemical processing
4. Other electrical driven processes such as microwave, plasma, ultrasound, etc.
5. Demo plants of CCU with special emphasis on carbon regeneration and purification in an industrial symbiosis setting
6. Creation of strong awareness networks between industry, SMEs and academic experts including industrial symbiosis managers and facilitators
7. Citizen awareness programs
8. Digital improvements at the level of plant operations, management of flows in industrial symbiosis
9. Training of new workforce in cross-sectorial approaches to new energy efficiency

Systems foresees a strong integration of different industrial sectors including not only process industry but also manufacturing industry, waste treatment and urban elements. As such this is already operational to a certain extent, but with large space for improvement, optimisation on the way toward really circularity of feedstock and energy. It is estimated that the symbiosis in the broad sense can contribute between 10 and 20% to GHG emissions reduction due to the better use of energy flows.

Furthermore, this kind of symbiosis delivers immediate strong economic benefits as long as logistic costs are not exaggerating. Logistic costs can often be covered by local/regional authorities as it makes the region attractive for investment in economic activities.

This is all strongly linked to process electrification in general and the development of specific electrochemical processes to replace some less efficient metal/chemical processes. As the carbon intensity of electricity goes to zero, strong GHG-emission reductions can be obtained via electrification. Attention must be paid to systems where electrons can be recovered leading to electricity creation in certain reactions (replacing e.g. heat production).

The industrial symbiosis, electrification and all other mentioned processes in the SET Plan Action 6 will benefit strongly from digital improvements at the level of feedstock and energy logistics, linking and optimising processes as at the level of tracking and tracing of flows (including smart grids).

Specific energy emissions and process emissions can be transformed into chemicals/fuels/minerals to reduce some inevitable CO_2 emissions and by making use of excess renewable energy streams (managed in a digital way).

Emerging technologies

10. Industrial – urban symbiosis
11. Electrical cracker/furnaces
12. Integrated oxidation-reduction reactions in one electrochemical system
13. New CCU-processes with less energy input, direct electron transfer and higher efficiency
14. Digital coordination between several plants on the same site including logistics (availability of feedstock and energy)
15. Digital support tools for feedstock (materials and energy) supply

8.3 Cement

Table 8-1 Cement decarbonisation path reduction potential

Decarbonisation path	Innovation/technology	Reduction potential
Alternative fuels (AF)	Technology exists / CAPEX requirements + access to waste sources for use as AF	60% AF use (of which 30% biomass) by 2030; 90% AF use (of which 50% biomass) by 2050
Alternative raw materials	Idem as above but access to alternative raw materials requires further research	
New cement clinkers		2% reduction in process emissions (2030) and 5% by 2050
Clinker substitution	Access to substitutes	Reduce clinker to cement ratio from 77% now to 74% in 2030 and 65% in 2050
Energy efficiency	Investment in waste heat recovery	4% improvement thermal efficiency (2030) and 14% in 2050
Carbon capture and storage	Several technologies under research / pilot: direct separation, oxyfuel technology	42% CO_2 reduction by variety of carbon capture technologies by 2050
Recarbonation	The reabsorption of CO_2 in concrete is a natural process; research is aimed at accelerating that process	Up to 8% saving in total CO_2 emissions for cement manufactured (assuming a 23% of process emissions of cement used being captured annually)

Table 8-2 Current status of Cement activities

Cement[52]	
Activity	**Current status**
3.1a Resource efficiency – alternative fuels	Currently, 48% of fuel needs on average in the EU are replaced by AF, avoiding 21 million tonnes CO_2 from primary raw materials. Some plants are at 95% AF use. No technical barriers; mostly regulatory (lack of landfill ban; permitting; taxation)
3.1b (iii) Resource efficiency – reducing cement ratio	Current ratio clinker to cement: 77%
3.2 Thermal efficiency	Converting preheater kilns to precalciner kilns + WHR from the cooler to generate up to 20% electricity needs for cement plant

8.4 Chemicals

The preliminary list of areas for key R&I activities in the chemical sector have been included in Fiches 4.1- 4.6 of Annex 2.

Activity 4.1 - Electrification

- Indirect use of electricity can be considered for heat and steam generation or upgrade. Electrification of high temperature chemical processes is one of the major R&I priority areas.
- Direct utilisation of electricity will require technology development for new electrochemical processes as well as for the integration of alternative energy forms such as ultrasound, microwave, plasma and light.

Activity 4.2 - Integrated production of Hydrogen with low carbon footprint

Technologies such as methane pyrolysis or photo-electrocatalysis are under development for the integrated production of hydrogen

Key R&I priorities include the optimisation of:

- reactor design
- efficient heating concepts for methane pyrolysis
- photocatalyst and photoelectrodes for photo-electrocatalysis.

Activity 4.3 - Plastic waste as an alternative feedstock

Different types of chemical processes can be used to recycle plastic waste: pyrolysis and gasification, depolymerisation process, and dissolution.

Major priorities for technical development include:

- operability including robustness allowing use of a wider range of plastics mixtures, process yield, and addressing reactor fouling for gasification and pyrolysis
- removal of impurities
- critical pre-treatment for depolymerisation
- batch to continuous processes for depolymerisation
- integration into existing chemical plant operations, either as feedstock or as monomer
- downstream separation and purification for depolymerisation.

Activity 4.4 - CO_2 */ CO as alternative feedstock*

Major priorities for technical development include for the chemical conversion step:

- catalyst design as a catalyst plays an essential role in the chemical valorisation of CO_2 which has a very low energy content and low reactivity. Objectives include the development of catalysts with high efficiency and selectivity, less prone to poisoning, enabling the utilisation of less purified CO_2 streams, enabling CO_2 valorisation processes at lower temperature and/or pressure.

[52] Targets to be met can be found in Section 6

- Optimization of reactor concepts, design and engineering for thermocatalytic, electrocatalytic, photo(electro)catalytic, biotech conversion routes.
- In addition, efficient capture and purification of CO_2 (as well as CO from off gases) streams from various sources are essential to improve energy efficiency and cost and enable subsequent, well performing CO_2 (and CO) valorisation reaction.

Activity 4.5 - Biomass as an alternative feedstock

Technological development is needed across all processing stages of biomass transformation into bio-based products:

- For the pre-treatment stage, aiming to efficiently prepare biomass for the conversion process:
- For the conversion stage - aiming to convert pre-treated feedstock into bio-based chemicals and materials - based on (thermo)chemical and (electro)catalysis processes, industrial biotechnology and biocatalytic processes.
- For the downstream processing stage, aiming to recover, separate and purify the intermediate product from biomass conversion.

Activity 4.6 - Process efficiency

Major R&I priority areas to improve process efficiency include:

- Process intensification, including
    - optimized reactor design concepts and equipment;
    - new catalysts.
- Separation technologies including further development of alternatives to distillation technologies (e.g. membrane technologies like pervaporation or membrane distillation) in addition to new distillation concepts.
- The optimisation of the design and engineering of separation operations would also include the development of specific materials.

The availability of tools supporting decision making from the early process/plant design phase of new processes to production management will be essential as well as the integration of digital technologies (see Systems Activity 2.3).

8.5 Iron & Steel

***Preliminary* list of technologies for the Iron & Steel sector**

Existing but not yet economically viable technologies

1. Integrated control system
2. Basic Oxygen Furnace Waste Heat and Gas Recovery
3. Exhaust gas heat recovery (furnace)
4. Combustion optimization (furnace)
5. Scrap Pre-Heating
6. Sinter Plant energy saving and Waste Heat Recovery
7. Stove Waste Gas Heat Recovery

Emerging technologies

8. Hydrogen based direct reduction
9. Electricity based direct reduction
10. Top Gas Recycling Blast Furnace
11. Iron Bath Smelting Reduction
12. Carbon Capture Usage and Storage (CCUS)
13. Circular economy approaches and technologies for enhanced recycling of steel (including scrap treatments, processing and cleaning for valorisation of low-quality scrap), enhanced utilisation of steel by-products (including slag treatments) and of residues (residue valorisation to reduce

demand for primary resources and reduce landfill volume) as well and increased recovery waste heat (including low-temperature waste heat) to increase resource and energy efficiencies in both primary and secondary steel production routes

14. Combination of the above technologies

8.6 Pulp & Paper

Direct carbon emissions of the pulp and paper industry (31 $MtCO_2$) are almost entirely derived from combustion of fossil fuels, with natural gas being responsible for about 75% of total emissions.

Going forward, the priority is to continue investing in energy and resource efficiency, to reduce the amount of energy needed. Until 2030 up to 2.5 $MtCO_2$ can be obtained making use of digitalisation and process innovations, e.g. reducing the amount of water to be evaporated and upgrading exhaust vapour as to allow effective use of heat pumps.

Secondly, an important role could be played by on-site, or nearly on-site, renewable energy sources (solar thermal, geothermal, on-site biogas production, renewable electricity, biomass).

From 2030 onwards the more radical innovations may lead to significant emission reduction, like integrated drying and heat integration, paper making without water or without water evaporation. Innovative energy efficient pulping processes will enhance indirect emission savings in the chemical industry as wood components currently used as a CO_2 neutral energy source may than be used to replace fossil-based feedstock. These more radical innovations are described in the Activity fiches.

Table 8-3 Pulp & Paper Energy Solutions Plan

Time Period	R&I Activities
Up to 2025: Best practices and Operational excellence	Lightning
	Data automation and control
	Improved mechanical dewatering
	Water savings: keeping the heat inside, inline water cleaning
	Drives and valves
	Adjust pressure levels
	Personnel training and behaviour analysis
	Improved heat (and cooling) integration - Heat recovery by heat exchangers
Up to 2030: Modular innovations	Mild repulping technologies
	More effective fibre refining technologies
	Innovative mechanical dewatering technologies
	Advanced process control e.g. by machine learning and digital twins
	Heat storage during breaks
	Electric drying assisting technologies
	Demand side flexibility
	Hydrogen to increase pulp mills product portfolio
	New systems eliminating or minimising the use of vacuum
After 2030: Breakthrough technologies	Integral drying and heat recovery processes
	Paper making without water
	Water removal without evaporation
	Mild pulping processes e.g. by Deep Eutectic Solvents
2025-2040: Cross-cutting innovations	Industrial components (boilers, pumps, valves, compressors, fans, conveyors… all of which systems typically contain motors and drives)
	Heat pump technologies
	Industry 4.0: digitalisation and machine learning
	System integration
	Industrial symbiosis
	Renewable energy systems (e.g. Solar thermal, hydrogen, nuclear)

Adapted from the CEPI Energy Solutions Forum plan[53]

Table 8-4 Preconditions and additional considerations for Pulp & Paper Targets

Pulp & Paper[54]	
Activity	**2025**
6.1 Integral drying and heat recovery processes	When sufficient competitively priced renewable electricity is available implementation may on mill level result in up to 40% energy savings of total paper process energy consumption.[55] Actual CO_2 savings will depend on the local energy mix.
6.2 Paper making without water evaporation	When sufficient competitively priced renewable electricity is available implementation on paper mill level may result in up to 20% saving of the drying energy so up 14% on total energy consumption, production without water may on mill level result in up to 50% saving of the drying energy so up 35% on total energy consumption. Actual CO_2 savings will depend on the local energy mix.[34]
6.3 Process optimisation and electrification (modular approach)	Progress depends on the specific modular technology and subject to the success of the 'competing technologies' being developed simultaneously. The modular approach may lead to 2-5% savings on the level of a process unit (one modular innovation) in an individual pulp or paper mill. Some modular innovations may be combined adding up to reach up to a maximum potential of 25% energy savings on mill level.[34] Actual CO_2 savings will depend on the local energy mix.
6.4 Mild pulping processes	Milder pulping technologies will not have an impact on the CO_2 emission of the pulp mills, as due to the utilisation of part of their biobased feedstock as energy source these mills are already CO_2- neutral. The impact will lay in the fact that at lower energy needs for pulping, these wood-based side streams will become available as valuable raw material source replacing fossil oil. Towards 2050 this may lead to up to 5 million tons of lignin becoming available as feedstock for biobased chemicals and materials. Roughly estimated, this would mean an energy saving of 200 PJ in the chemical industry (energy consumption of fossil feedstock for aromatic hydrocarbon chemicals, i.e. about 43 GJ/t with reference to benzene, toluene and xylene)[56]
6.5 Onsite renewable energy conversion	N/A. Demonstration and implementation of innovative technologies up to 2030.
4.5/ 6.6 Biomass as alternative feedstock	Continuous development, demonstration and implementation of various new biobased products from forest biomass. The share of emerging bio-based products (other than pulp and paper) will substantially increase as to contribute to the sectors ambition of 50% more added value in 2050. (currently 3% of European pulp and paper industry sector turnover).

[53] https://www.cepi.org/energy-solutions-forums-objectives-and-challenges/
[54] Targets to be met can be found in Section 6
[55] Total Energy consumption (incl. Net Bought electricity) in the pulp and paper industry is: 1 312 508 TJ. Total CO_2 emissions in the pulp and paper industry (2019): 31.1 Mton. Savings obtained with the activities in this fiche only hold for the paper production part. – Cepi Key Statistics 2019.
[56] Tracking industrial energy efficiency and CO_2 emissions, IEA, in support of the G8 Action plan, 2007.

9 ANNEX 2: R&I ACTIVITY FICHES

9.1 Heating and Cooling Activity Fiches

9.1.1 Activity 1.1 – Thermal energy upgrade from low temperature to high temperature

Title: Heat upgrade from low to high grade - Heat pumps		
TG: Heat & Cold	**Activity No: 1.1**	**Activity leader: ETN Global/ EUTurbines**
Targets: **Short term:** By 2025, develop and demonstrate solutions enabling small and large industries to cost effectively reduce their energy consumption by 5% by cost-effectively upgrading excess heat for use elsewhere in the process (to TRL 7 for heat upgrade to temperatures up to 200/250°C and to TRL 6 for temperatures above 250°C). **Long-term:** 2030 and 2050 targets see Section 6 in main document		**Action 6 monitoring activities will draw on relevant industry publications.** Review of relevant industry information **Possible primary data collection to monitor progress (not monitored under SET Plan)** The deployment of heat pumps will be monitored using the cumulative installed capacity (MW) as well as the saved energy (GWh). The heat pump efficiency will be assessed using the coefficient of performance (COP). Finally, the avoided emission of CO_2 will also be reported.

Description:
This activity is related to heat pumps converting low-temperature thermal energy (typically available at 50°C-120°C) into higher temperature heat (at temperature up to 200/250°C and >250°C). The development and implementation of pilot and demonstration of innovative heat pumps (2-3 MW) to make cost-effective use of waste heat at very high efficiency will be pursued. Research activities would include but are not limited to:

- Improving the understanding of internal energy flows in a given system (e.g. Sankey Diagram) and integration with irreversible thermodynamics to enable new heat integration and recovery strategies.
- Achieving safe, controlled and efficient recovery of heat from substances which are very difficult to handle and control (high temperature, high volumes, highly aggressive - fouling/deposits/corrosion, compact hot solids or granulated particles).
- Transfer of energy flows with various heat transfer media (water/steam, oil, salts, gases, solids, etc.).
- Development and demonstration of innovative technology concepts for production process.
- System configurations for different thermodynamic cycles and operating modes.
- Demonstration of heat pumps operability.
- Verification of components performance.
- Demonstration of process energy savings.
- Demonstration of heat pump efficiency levels.

Impact
(see Note at end of Fiche 1.3: assumptions for impact calculation)
Reduction of process energy demand by 5%
Primary energy saving potential in percentage and in ktoe/a (assuming full deployment in the EU27 + UK) At least 3.5% (1750ktoe/a) only relative to the steel industry sector. Higher primary energy saving assuming the deployment of the technology in other industry sectors.
GHG emission saving potential in percentage and in ktCO2eq/a (assuming full deployment in the EU27 + UK) At least 1.2% (4575 ktCO2/a) of the steel industry sector (the data consider the deployment of the technology only to the steel industry sector).

Technology Readiness Level (TRL): Heat pumps converting low-grade heat to temperatures up to 200/250°C and starting from TRL5 to achieve TRL7; Heat pumps converting low to high grade above > 250°C starting TRL 3 to TRL 6

Total budget required €7-8 million per project. Additional budget is required to achieve TRL8 and 9.

Expected deliverables	• Optimised cycles for different low-grade heat opportunities, • Design tools,

	• (new) working fluid properties, • Cycle optimisation in terms of efficiency and capex, • Engineering, construction and commissioning of pilot plant, • Component and module concepts and enhanced design tools, • Innovative heat pump concepts, • Balance of plant as required by concept, • Technologies for an exergy-optimised energy supply, • Higher heat transfer coefficients, • Higher process and resource efficiency in processing and increased energy efficiency (e.g. Thermal driven separation technologies), • Significant increase of waste heat potential of specific process technologies requesting a constant and lower energy demand (e.g. By batch-to-continuous approach) smoothening the heat demand profile with positive impacts on the energy supply • New working fluids, which are suitable for use in heat pumps supplying heat in the range of 150°C to 250°C.
Timeline	36 months

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
Energy intensive industry, turbomachinery industry, heat exchanger industry, heat pump industry, control and monitoring OEM's, universities and research institutes.	Mix of private equity/debt and public (national and European) grants/loans/ guarantees.	N/A

Gaps: Heat pumps have to be used for conversion of lower to higher grade heat. Their application to industrial size and standards have not yet been verified and shall be demonstrated in the turn of this action.

TECHNOLOGICAL BARRIERS: Several obstacles should be considered: the non-existence of nearby heat sinks or end-use applications, time discrepancy of energy generation and demand, and severe operating conditions. Besides, conditions like chemical composition of the waste heat sources may vary among sectors and companies and could put in danger the smooth operation of the proposed technical solutions.

FINANCIAL AND ADMINISTRATIVE BARRIERS: They are mainly related to the economic feasibility of the solutions (return on investment, payback time) and availability of investment funds, priority of the core business and uncertainty of the economic future or administrative efforts. Finally, many companies lack business knowledge or specialized staff.

9.1.2 Activity 1.2 – Waste heat to power (low and high temperatures)

<table>
<tr><th colspan="3">Title: Use of low/medium temperature waste heat (120 - 350ºC) to generate electrical power at high efficiency.</th></tr>
<tr><td>TG: Heat & Cold</td><td>Activity No: 1.2a</td><td>Activity leader: ETN Global/ EUTurbines</td></tr>
<tr><td colspan="2">Targets:

Short term: By 2025, develop and demonstrate (up to TRL 7) new and novel solutions enabling small and large, industries to cost effectively (€/kW) recover 10% of the total amount of low/medium temperature waste heat (100-300˚C) while proportionally reducing GHG emissions (tons of avoided CO_2 emissions).

For long-term 2030 and 2050 targets see Section 6 in main document</td><td>Action 6 monitoring activities will draw on relevant industry publications. Review of relevant industry information

Possible primary data collection to monitor progress (not monitored under SET Plan)
Monitoring of the waste heat recovery (GWh) and GHG emissions (tons CO_2) with the proposed technologies compared to the conventional approach. The efficiency of WHR technologies will be assessed using waste heat source utilization efficiency (%). Finally, the specific capital cost will be tracked (€/kW)</td></tr>
</table>

Description:
This activity is related to low/medium-temperature thermal energy conversion from (harsh) industrial environments to generate power (mechanical or electrical) using advanced thermodynamic cycle systems. The development of pilot and demonstration of innovative power generation concepts, which can be combined with further cascaded heat generation if possible/relevant will be pursued. The concepts at the basis of suitable technologies include but are not limited to, organic Rankine cycle (ORC)/Trilateral Flash cycle (TFC), sCO_2 cycles, thermo electric conversion, magneto caloric conversion, Stirling cycle, etc.
R&I activities are different depending on the heat source temperature and targeted power output, as components require different technologies. Larger systems (MWs) usually are process-tailored solutions and are currently at higher TRL. Small systems (KWs) also have a large potential and can reach cost-effectiveness via standardization, but their starting TRL is lower.
Fluid mixtures as working fluids and thermohydraulic coupling of the power plant with thermal energy storage should are considered. Demonstrators of large and small systems for low and high waste heat temperature sources depending on target industrial process will be developed and realized. Research activities will include but will not be limited to:

- Improving understanding of internal energy flows in a given process (e.g. Sankey Diagram) and integration with irreversible thermodynamics to enable new heat integration and recovery strategies.
- Achieving safe, controlled and efficient recovery of heat from media, which are very difficult to handle and control (high temperature, high volumes, highly aggressive- fouling/deposits/corrosion, compact hot solids or granulated particles).
- Characterizing the energy transfer with various heat transfer substances (water/steam, oil, salts, gases, solids).
- Demonstration of the operability of waste heat power plants.
- Verification of components performance.
- Further development of components for small ORC systems (expanders, heat exchangers, pumps).
- Evaluation of new working fluids (pure and mixtures).
- Evaluation of innovative cycle configurations.
- Demonstration of the possibility of achieving low LCOE.
- Demonstration of the possibility of achieving low CAPEX.
- Demonstration of the possibility of achieving high thermal energy conversion efficiency.
- Demonstration of *ad hoc* configurations for different operating modes.
- Evaluation of reconfigurable / open architectures and plug & play solutions.
- Demonstration of cluster-type, multi-module small & flexible waste heat to power units for retrofitting in complex industrial waste heat streams.

The target is to identify the best technologies, based on a number of criteria set up at the beginning of the project, given that so far economic viability is often unsatisfactory.

Impact:
(see Note at end of Fiche 1.3: assumptions for impact calculation)

Recovery of up to 10% of the low/medium temperature waste heat as electric or mechanical power, and cascaded thermal energy use if possible

Primary energy saving potential in percentage and in ktoe/a (assuming full deployment in the EU27 + UK)

At least 6.9% (3500ktoe/a) only relative to the steel industry sector. Higher primary energy saving assuming the deployment of the technology in other industry sectors.

GHG emission saving potential in percentage and in ktCO2eq/a (assuming full deployment in the EU27 + UK)

At least 2.4% (9150 ktCO2/a) of the whole industry sector (the data considers the deployment of the technology only to the steel industry sector).

Technology Readiness Level (TRL): From current level TRL 1-4 to TRL 4-7 for small systems and from TRL 4 to 7 for large systems. (TRL depends also on how challenging the technology of the components is e.g. low temperature/pressure vs high temperature/pressure).

Total budget required

TRL 1-4: 3 M€ per project; TRL 4-7: 14 M€ per project; Additional budget is required to achieve TRL 8 and 9.

Expected deliverables	***On system level:*** • Optimised cycles for different exhaust temperature levels, and CAPEX • Multi-module optimization models in terms of efficiency and CAPEX • Design tools including dynamic simulation and controls • New working fluids (including mixtures) and their models • Engineering, construction and commissioning of pilot plant ***On component level:*** • Component and module concepts and enhanced design tools, • Advanced sealing technologies for large scale sCO_2 and ORC applications • Waste heat recovery heat transfer and expander/pump technologies Balance of plant as required by concept
Timeline	60 months

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
Energy-intensive industry, turbine industry, universities, research institutes	Mix of private equity/debt and public (national and European) grants/loans/guarantees.	*N/A*

Gaps: Ambitious development necessary for above listed deliverables which contrasts with mature technology of power generation based on water/steam. Depending on the quality of the excess heat, novel concepts and approaches need to be explored. There is the need for new component developments such as expander and pumping units, heat exchangers, etc. In addition, system control and safety aspects have to be taken into account to advance the concepts from lower TRL to higher TRL, depending on the starting level.

<table>
<tr><th colspan="3">Title: High temperature waste heat recovery to generate electrical power at high efficiency</th></tr>
<tr><td>TG: Heat & Cold</td><td>Activity No: 1.2b</td><td>Activity leader: ETN Global/ EUTurbines</td></tr>
<tr><td colspan="2">Targets:

Short term: Develop and demonstrate (to TRL 7) by 2025 solutions enabling small and large, industries to cost effectively (€/kW) recover 20% of total available high temperature waste heat (>300˚C) while striving to reduce GHG emissions proportionally (tons avoided CO_2 emissions).
For long-term 2030 and 2050 targets see Section 6 in main document</td><td>Action 6 monitoring activities will draw on relevant industry publications. Review of relevant industry information

Possible primary data collection to monitor progress (not monitored under SET Plan)
Monitoring of the waste heat recovery (GWh) and GHG emissions (tons CO_2) with the proposed technologies compared to the conventional approach. The efficiency of WHR technologies will be assessed using waste heat source utilization efficiency (%). Finally, the specific capital cost will be tracked (€/kW)</td></tr>
</table>

Description:
One example of this is supercritical CO_2 cycle power plants – these have been studied for nuclear and solar applications where they are expected to achieve high cycle efficiencies combined with compact turbomachinery leading to reduced environmental and physical footprint. However, sCO_2 cycle power plants for waste heat recovery have virtually no deployment. The use of CO_2 technology for waste heat recovery requires development of turbomachinery, heat exchangers and bottoming cycle components (e.g. fluid pumps and compressors) in addition to cycle configuration optimization. For the given temperature level and amount of discharged thermal energy from the industrial process, an initial comparison with conventional technology will provide the potential in terms of thermodynamic efficiency and economic benefit. Turbine concepts, enhanced design tools, new sealing technologies, high-pressure low-cost heat exchangers, advanced blade technology, advanced CO_2 blends as working fluids and bottoming cycle components need to be developed. Another critical element is the waste heat recovery unit which transfers the waste heat to the sCO_2 working fluid. The waste heat is usually available in an unfriendly form, with limited space, limited pressure drop, harsh fluids and gases, and multiple streams. All these challenges need to be overcome with an affordable, safe, and reliable heat exchanger. Containing material properties in association with sCO_2 (pure or blends) and specific issues (corrosion, lifetime, creep, fatigue) need to be assessed.
The integration of sCO_2 concepts with high temperature storage (>400°C) has to be developed and demonstrated in order to smooth the intermittent character of the recoverable energy flows (such as low-cost materials with high thermal inertia, phase change materials, fluidized beds, etc.).
The detailed plant layout needs to be optimised followed by engineering, construction and commissioning.
Controls of the sCO_2 power block need to ensure flexibility and safety of operation as well as maximise the waste heat utilisation in symbiosis with the topping industrial process.

Impact:
(see Note at end of Fiche 1.3: assumptions for impact calculation)
Transformation of high temperature waste into usable power **at an efficiency level of about 20%.**
Primary energy saving potential in percentage and in ktoe/a (assuming full deployment in the EU27 + UK)
At least 13.8% (7000ktoe/a) only relative to the steel industry sector. Higher primary energy saving assuming the deployment of the technology in other industry sectors.
GHG emission saving potential in percentage and in ktCO2eq/a (assuming full deployment in the EU27 + UK)
At least 4.8% (18300 ktCO2/a) of the whole industry sector (the data consider the deployment of the technology only to the steel industry sector).

Technology Readiness Level (TRL): Progress from TRL 4 to TRL 7.

Total budget required 80M€ (costs determined by size of demonstrator). Additional budget is required to achieve TRL8 and 9.

Expected deliverables	**Demonstrator (10MWe)** of the CO2 Waste Heat Recovery cycle ***1) System level deliverables:***

	evaluate optimised cycle for given exhaust temperature levels, *design tools including media properties, dynamic simulation and controls* *estimations on cycle optimisation in terms of efficiency and capex,* *engineering, construction and commissioning of pilot plant* *demonstrate operability of SCO2 cycle* *verify performance of components* *demonstrate potential to produce a low LCOE* *demonstrate potential for cycle efficiency* *configuration for different operating modes* *reconfigurable / open architecture / plug & play solution* ***2) Component level deliverables:*** *Development of turbine concepts (definition of casings, arrangement, fix points, blade path, speed, etc).* *Enhance turbine design tools* *Development of new sealing technologies for sCO2 requirements,* *advanced blade technology profiles based on changed fluid properties such as viscosity, speed of sound, etc.* *Develop robust last stage blades matching cycle specific requirements,* *Development of compact and modular high performance heat exchangers (waste heat recovery unit, recuperator, condenser/gas cooler)* *Enhance heat exchanger design tools* *Development of control equipment, strategies and electronics* *Considering the fluid specific requirements with respect to corrosion/erosion, adapt/develop appropriate and cost-effective materials, coatings and manufacturing methods for sCO2 applications incl. Material tests (corrosion, life time, creep, fatigue)* *material tests (corrosion, life time, creep, fatigue)*
Timeline	36 months

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
Energy-intensive industry, turbine industry, universities, research institutes	Mix of private equity/debt and public (national and European) grants/loans/guarantees.	N/A

Gaps: Ambitious development necessary for above listed deliverables which contrasts with mature technology of power generation based on water/steam

Note: Assumptions for impact calculation (applicable to fiches 1.2, 1.3, 1.4):
Primary energy saving potential in percentage and in ktoe/a (assuming full deployment in the EU27 + UK): 7000 ktoe/a

Total Consumption of Energy in Industry 2015 EU27 + UK = 272.5 Mtoe/a

Iron and steel energy consumption = 50.8 Mtoe/a

Reduction related to the steel industry sector = - 13.8%[57]

GHG emission saving potential in percentage and in ktCO2eq/a (assuming full deployment in the EU27 + UK): 18.3 MtCO2/year

Total Production EU27 + UK = 4400 MtCO2/year

Reduction = -0.4%

8.5 % related to industrial processes.

[57] Assuming energy conversion efficiency not lower than average generating efficiency of thermal power plants in the EU27 + UK.

Reduction related to the industry sector = -4.8%[58] http://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics

9.1.3 Activity 1.3 – Waste and renewable heat to cold generation

Title: Waste and renewable heat to cold generation		
TG: Heat & Cold	**Activity No: 1.3**	**Activity leader: ETN Global/ EUTurbines**
Targets: **Short-term:** By 2025, develop and demonstrate (to TRL 7) cost effective waste heat recovery and renewable energy integration for cold generation solutions. For long-term 2030 and 2050 targets see Section 6 in main document		**Action 6 monitoring activities will draw on relevant industry publications.** Review of relevant industry information **Possible primary data collection to monitor progress (not monitored under SET Plan)** Monitoring of the waste heat recovery potential and GHG emissions with the proposed technology compared to the conventional one.

Description:
To reduce the environmental impact and make the industrial sector more competitive, several actions aimed at increasing the efficiency of the cooling systems and reducing costs, increasing the harnessing of available waste heat, and coupling the cooling systems with renewable energy sources can be pursued. In particular:

- Improvement of system efficiency.
- Improving the control system and operating strategies; developing internal recoveries for vapour compression refrigeration plants; developing and applying advanced organic fluids and novel heat exchangers for single and double effect absorption refrigeration systems.
- Hybridization with renewable energy sources.
- Hybridizing the absorption refrigeration systems with on-site solar thermal plants plus a thermal storage and/or harnessing the waste heat made available by the industrial process; hybridizing vapour compression refrigeration systems with PVs or other on-site renewable power generation systems.

Impact:
Cooling and cryogenic systems in industrial processes are responsible for about 4.5% of the total greenhouse gas emissions and consume nearly 15% of the worldwide electricity production.
Primary energy saving potential in percentage and in ktoe/a and **GHG emission saving potential in percentage and in ktCO2eq/a** to be calculated based on the application.

Technology Readiness Level (TRL): From current TRL 4 to TRL 7.

Total budget required: 2 M€ TRL 4 to 5; 14 M€ TRL 5 to 7. Additional budget is required to achieve TRL8 and 9.

Expected deliverables	Improved thermodynamic cycles and components. Full integration of renewable energy generation in a refrigeration system for the industrial environment. Wide operating range of ambient conditions. Use of environmental-friendly fluids.	
Timeline	36 months	
Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
Energy-intensive industry, turbine industry, universities, research institutes	Mix of private equity/debt and public (national and European) grants/loans/guarantees.	N/A

[58] Assuming energy conversion efficiency not lower than average generating efficiency of thermal power plants in the EU27 + UK.

9.1.4 Activity 1.4 – Polygeneration (heat, cold, electrical power) and hybrid plants

<table>
<tr><th colspan="3">Title: Hybrid plants for waste heat upgrade integrating renewable energy into industrial plants and processes</th></tr>
<tr><td>TG: Heat & Cold</td><td>Activity No: 1.4a</td><td>Activity leader: ETN Global/ EUTurbines</td></tr>
<tr><td colspan="2">Targets:
Short term: By 2025, develop and demonstrate (to TRL 7) cost effective excess heat/cold recovery solutions and integration of renewable heat in the industrial processes.

For long-term 2030 and 2050 targets see Section 6 in main document.</td><td>Action 6 monitoring activities will draw on relevant industry publications. Review of relevant industry information

Possible primary data collection to monitor progress (not monitored under SET Plan) Monitoring of the waste heat recovery potential and GHG emissions with the proposed technology compared to the conventional one.</td></tr>
</table>

Description:
Development of hybrid plant integrating and potentially storing renewable electricity and heat (e.g. solar thermal, bioenergy, geothermal, renewable electricity, and renewable hydrogen) into industrial plants and processes reducing the reliance from external energy and utilizing energy storage technologies to enable timely shift to match availability and demand. Demonstration of the technology in a relevant environment increasing the TRL level towards more effective applications. Research activities may include but not be limited to the following:

- Achieving safe, controlled and efficient recovery of heat from media, which are very difficult to handle and control (high temperature, high volumes, highly aggressive- fouling/deposits/corrosion, compact hot solids or granulated particles).
- Transfer of energy flows with various heat transfer media (water/steam, oil, salts, gases, solids, etc).
- Polygeneration of cold, heat & power based on left- and right-handed Joule and Rankine cycles and various working fluids (e.g. sCO_2, ORC, NH_3, N_2, Air).
- Development and demonstration of new solutions for the integration of renewable energy technologies in industrial process heat applications

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Impact:
(see Note at end of Fiche 1.3: assumptions for impact calculation)
Primary energy saving potential in percentage and in ktoe/a (assuming full deployment in the EU27 + UK) 13.8% (7000ktoe/a) only relative to the steel industry sector. Higher primary energy saving assuming the deployment of the technology in other industry sectors.
GHG emission saving potential in percentage and in ktCO2eq/a (assuming full deployment in the EU27 + UK)
4.8% (18300 ktCO2/a) of the whole industry sector (the data consider the deployment of the technology only to the steel industry sector).

Technology Readiness Level (TRL): From current TRL 4 to TRL 7.

Total budget required: 30M€ TRL 5 to 7. Additional budget is required to achieve TRL8 and 9.

Expected deliverables	Improved thermodynamic cycles. Full integration of renewable energy generation in a combined heat and power/polygeneration system for the industrial environment. High electrical efficiency of more than 65% and total thermal efficiencies of more than 90%. Demonstration of renewable technologies for industrial process heat applications with focus on medium and high temperature thermal energy demands (above 150ºC) Wide operating range of ambient conditions. Keeping NOx emissions complying with EU legislation.
Timeline	36 months

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
Energy-intensive industry, turbine industry, universities, research institutes.	Mix of private equity/debt and public (national and European) grants/loans/guarantees.	…

Title: Advanced compact Combined Heat and Power - plants of industry scale		
TG: Heat & Cold	**Activity No: 1.4b**	**Activity leader: ETN Global/ EUTurbines**
Targets: Short term: By 2025, develop and demonstrate (to TRL 7) cost effective excess heat/cold recovery solutions For long-term 2030 and 2050 targets see Section 6 in main document		**Possible primary data collection to monitor progress (not monitored under SET Plan)** Monitoring of the waste heat recovery potential and GHG emissions with the proposed technology compared to the conventional one.

Description:
Further development of advanced compact Combined Heat and Power (CHP) / polygeneration plants of industry scale for generation of electricity, steam, heat (i.e. polygeneration) for industrial application with fuel conversion ratios > 90%.
Compact CHP plants are usually driven by industrial gas turbines and a combination of steam turbines and recovery steam generators which need to further be developed for enhancing the fuel conversion rate of compact CHP-plants up to 85-90%. Special requirements are operational and fuel flexibilities including low calorific, renewable biomass or synthetic gases. Fuel flexibility must also cover liquid fuels applications. The project should build on on-going projects at component level and extend the results to plant level, lifting the TRL from 3-5 to 5-7.

Impact:
(see Note at end of Fiche 1.3: assumptions for impact calculation)
Primary energy saving potential in percentage and in ktoe/a (assuming full deployment in the EU27 + UK)
Industrial CHP-Plants can be widely used for all energy intensive industries such as steel, pharma, chemical and automotive industries with a saving potential of > 25% (~12000ktoe/a) in all industry sectors.
GHG emission saving potential in percentage and in ktCO2eq/a (assuming full deployment in the EU27 + UK)
Extensive GHG-emissions reduction potential estimate > 8% (> 32000 ktCO2/s) after full deployment of the technology in all relevant industry sectors.

Technology Readiness Level (TRL): From component level 3-5 (running projects) to plant level 5-7

Total budget required: 3 M€ TRL 3 to 5; 7 M€ TRL 5 to 7. Additional budget is required to achieve TRL8 and 9.

Expected deliverables	Improved thermodynamic cycles with respect to generation of process steam, heat and cold. Improved plant components optimized for compact CHP/polygeneration cycles Wide operational flexibility ranging from 25% to 100% electric power. High ramp rates. Keeping NOx emissions complying with EU legislation. Validation of component improvements in real plant environment.
Timeline	36 months

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
Energy-intensive industry, turbine industry, universities, research institutes.	Mix of private equity/debt and public (national and European) grants/loans/guarantees.	*N/A*

Gaps:
The focus is on components only, which need to be adjusted to the operating scenarios. At present sources of excess heat of industrial power generation are not fully explored. In particular, problems have to be overcome since industrial CHP cycles are dominated by the steam and heat demands for the industrial processes. A pilot demonstration is needed to gather all improvements achieved, as proposed above.

9.2 System Integration Activity Fiches

9.2.1 Activity 2.1 - Industrial Symbiosis: between energy intensive industries to valorise energy losses streams and better manage energy globally

<table>
<tr><th colspan="3">Title: Industrial Symbiosis: between energy intensive industries to valorise energy losses streams and better manage energy globally</th></tr>
<tr><td>TG: Systems</td><td>Activity No: 2.1</td><td>Activity leader: A.SPIRE</td></tr>
<tr><td colspan="2">Targets:

Understanding of the industrial systems, covering energy/heat/cold/materials/by-products cross-sectorial flows, including valorisation of output. To characterise the market opportunities for heat and power supply to the local, regional and national energy markets through the development of a series of operating scenarios based on industrial symbiosis. These will include the potential opportunities for the process industry units to provide services to the operation of heat and power networks beyond the fence-line. Development and demonstration of solutions, including the needed local logistics, enabling small and large industries to reduce their total energy consumption by 10 to 20% while striving to reduce GHG emissions proportionally</td><td>Action 6 monitoring activities will draw on relevant industry publications. Review of relevant industry information

Possible primary data collection to monitor progress (not monitored under SET Plan) Key performance indicators will be developed which will allow comparison to a given benchmark; such as:
Specific energy consumption per ton of produced product, base line 2015
Standardized indicators measuring energy and resource efficiency actions under real production conditions and different processes
Identify and select appropriate assessment methodologies and impact parameters and further develop and demonstrate in real industrial pilot case, suitable macro and meso-indicators across sectors</td></tr>
</table>

Context:
Most processes generate by-products (process gases or condensed material) as well as energy losses, showing global energy efficiency well below 100%. Typically, the energy losses can reach 40 to 50% in cement production, 50% in steel, 55% in glass, 20% in refining, 65% in wood products.
Industrial symbiosis involves the exchange of material (including water) and/or energy flows between two or more production sites or sectors, thereby improving energy and resource efficiencies.
Industrial symbiosis is complex from a technological standpoint, but also from the operational standpoint: in order to be materially possible, safe, and cost effective for all partners, and for society as a whole, the symbiosis will require a very good coordination regarding production cycles, management of unexpected stoppages, etc.
Industrial symbiosis also requires extra logistics (need for extra regional investments) to enable the exchange of flows. Furthermore, a trusted symbiosis facilitator is needed to manage the exchange of flows, the liability, economics etc. in a new business model.

Recommended action: Identification of an appropriate quantification methodology for industry symbiosis

There is a need for quantification methodologies that can further assess the recovery potential of the energy losses and by-products and so enable an analysis of both heat and material integration of industries. An exergy-based analysis is capable of this, without revealing process sensitive information, but there are challenges with material streams crossing production unit limits, and when the product is not stable. In several cases intermittent treatment (e.g. upgrading) steps will be needed as well.

Exergy Analysis can be used in many ways to improve efficiencies: process design and optimization, on-line thermo-economic diagnosis, rational cost assessment of plant products, evaluation of alternatives among various designs or operation decisions and profitability maximization, energy (exergy) audits, and setting rational legislation about commercially efficient solutions

All the above will facilitate price setting of interchanged commodities, which will lay the foundation of Industrial Symbiosis scenarios.

<u>Actions and projects could cover:</u>

- For analysing and characterising the sources of energy and material losses (e.g. amount, composition, temperature, impurity, fluctuation including also ranges) systemic models of dynamic systems must be developed to easily simulate time dependent technical constraints but also environmental, social, legal and economic aspects.
- Determining the production flexibility to prevent peaks and to coordinate the sources and demands to optimise yearly the energy and material fluxes between the different plants. Optimization of matches.
- Determining storage technologies and strategies to harmonize energy use for fluctuating inputs (e.g. wind, converter gas) and variable (batch) process demands. These energy storage systems must be efficient (not degrade the stored energy for long periods - several hours or days), flexible (short response times) and easily transportable (at least over limited distance).
- Determining energy conversion technologies and strategies as well as the most suitable carriers to improve the accordance of demands and sources of energy.
- Fusing and combination of existing energy management systems for electricity and gas with the new management systems for the energy loss fluxes.
- Expanding the flexibility of existing energy management systems and connecting them digitally to production planning tools to enable what-if calculations for strategic planning of process changes in the connected plants.
- To connect individually existing management systems to enable a cross-plant and cross-industry optimisation.
- To provide a commercial framework, which fully puts the operating facility in the setting of commercial markets for heat and power. And then to extend the rule-based system for maximising operational profitability within the context of external markets and the practical deployment of industrial symbiosis principles. This technical and commercial optimisation will be set within the boundary conditions determined by the legislative frameworks
- Linking synergies and by-product waste streams to several technologies (existing, newly developed, development needs) to review performance (environmental, socio-economic, resource)
- Engage and review the governance and facilitation mechanisms needed to facilitate IS exchange
- Identify concrete pathways to facilitate and coordinate the implementation of new initiatives on industrial symbiosis. This should include an assessment of the mechanisms to create incentives for the industry and align it with the delivery of public and environmental benefits.
- Identification of an increased number of identified potential business cases based on the integration of "alternative" streams (such as heat, waste, water, by-products and gaseous effluents) from business and public entities.

Impact:

- Reduce fossil fuels use by up to 20% depending largely on the envisaged industrial sectors
- Enable cost-saving optimizations of energy and resources supply and demand
- Lay down the foundation for large deployment of the sustainable cross-sectorial energy and material networks focusing on streams of energy losses and by-products.

Primary energy saving potential in percentage and in ktoe/a (assuming full deployment in the EU27)

GHG emission saving potential in percentage and in ktCO2eq/a (assuming full deployment in the EU27)

To be provided at a later stage as it needs to be assessed further by the sectors. Current analysis is not yet consolidated.

Technology Readiness Level (TRL): 4-5 at first stage to be up scaled to 7-8 TRL

Total budget required: €4-5 m for low TRL and €15-20 million for high TRL projects (without the necessary logistics which depend strongly on local situations)

Expected deliverables (preliminary list of some of the deliverables)	Database of archetypes for typical facilities across P4Planet industrial (sub)sectors, identifying the waste heat rejection streams and heat demands, the type of facility, and capacity. (P4Planet initiative includes 10 sectors, relevant to systems, some of which are shared with Action 6. It includes cement, ceramics, chemicals, engineering, minerals and ores, non-ferrous metals, steel, and water)

	• Database of technical characteristics and specific costs (investment and operational) for heat recovery, storage, conversion and upgrade technologies • Report on Clustering and Many-to-many matching of Heat Sources with Waste Heat Valuable Temperatures (WHVTs) for Industrial Symbiosis • Design of Demonstration Energy Management Networks • Validation and Assessment of Simulated Energy Network Performance • Enhancement of Innovative Energy Storage, conversion, transport, transformation Technologies and Solutions • Report on the mathematical modelling approach and result framework for the demo networks • Outline and suggest methodological approaches to review organizational, political and institutional enablers and constraints • Provide indicators for performance improvements from IS networks • Estimation of the potential reduction in operational and logistics costs from a wide implementation of industrial symbiosis Evaluation of the potential economic and environmental impact (including resource and energy savings, waste reduction) of industrial symbiosis, based on LCA and Business Models
Timeline	Projects of 36 to 48 months are recommended. First stage would need a timeline of 5-6 years. If first stage successful, a subsequent second stage should need 4-5 years of development. Some IS sites are already well developed and can move faster than others still under development. So, different Symbiosis Readiness Levels (SRLs) will be considered.

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
• *It might be beneficial to all EU countries.* • *In all cases, industrial sites & parks and clusters are at the core of those initiatives as they are the most promising locations in which IS could be applicable.*	• Funds at EU level should be guaranteed in order to achieve true cross-sectorial EU dimension of technologies development and demonstration (e.g. Horizon Europe, notably the Processe4Planet partnership) • Other complementary funds or tools could cover specific territorial interests (e.g. national or regional funds) or support deployment (e.g. Investment and financial instruments from EIB, ETS Innovation Fund ...)	*To be completed at a later stage* *Local financial by regions/cities authorities might help in the facilitation management as well in the deployment of needed logistics.*

Gaps:

- Trust between the parties and toward the enabler
- Flows need to match with each other (systems to manage this are needed whereas excess flows involved need to match with other organization/plants requirements)
- Flows that can't be used in a local proximity and need to be converted to make them transportable over a longer distance (Community of Practice)
- Integration with urban symbiosis
- In some cases, thermal aspects of water need to be taken into account as well

Industrial symbiosis initiatives involve the exchange of material and/or energy flows between two or more production sites. The realisation of this concept usually faces a series of technological (in some cases even tailor-made) and non technological challenges. Besides, to make technical solutions marketable, demonstration scale activities are mandatory to make them more visible and use them to showcase them as a reference for a large number of industrial locations across the EU. As a result, the IS concept should start by TRL 4-5 to end up at TRL 7-8 as a second stage. Some sites can move to SRLs of 8-9.

9.2.2 Activity 2.2 - Non-conventional energy sources in process industry including carbon capture and use

<table>
<tr><th colspan="3">Title: Non-conventional energy sources in process industry including carbon capture and use</th></tr>
<tr><td>TG: Systems</td><td>Activity No: 2.2</td><td>Activity leader: A.SPIRE</td></tr>
<tr><td colspan="2">Targets:
Develop and demonstrate solutions enabling small and large industries to reduce their energy consumption by 20% while striving to reduce GHG emissions proportionally. This is based on the development of processes using renewable energy coming from electrification with a focus on energy mix, energy fluctuation and efficiency of the new developed processes.
Depending on the carbon intensity of the electricity GHG-reductions can still strongly be decreased (up to 100% in 2050).
Reduce the CO_2 emissions from energy use and especially from process emissions via carbon capture and use. The use is based on mineralization, conversion into fuels, chemicals, polymers, materials.</td><td>Action 6 monitoring activities will draw on relevant industry publications. Review of relevant industry information
Possible primary data collection to monitor progress (not monitored under SET Plan)
Degree of process-electrification
Increase of energy efficiency (via process intensification)
Increase of energy productivity
Degree of fossil energy replacement by renewable energy
Degree of digital optimization of energy mix and fluctuations (flexibility)
Degree of CO_2 converted into new materials, fuels and chemicals and the GHG-reductions compared to the classical production process of those materials, fuels and chemicals.</td></tr>
</table>

Description:
Intensive industries face many challenges with regard to energy consumption, use, planning and integration. By definition this kind of industry is high energy demanding which requires extra efforts towards reducing the consumption of conventional energy sources based on carbon. On the one hand, renewable energies are offering more and more adapted and flexible features to be integrated in large industrial plants. Furthermore, non-conventional energy sources might also contribute to decrease the carbon footprint of the intensive industries. Even beyond, the combination of both renewable sources plus non-conventional sources could end up with significant improvements with regard to GHG emissions and environmental indicators. However, changing to renewable sources, mainly sustainable electricity, has several large challenges:

- The electricity demand will increase significantly
- The costs of these (often basic) products could increase dramatically if electricity prices remain high (however, recent trends in costs of renewables, such as solar PV, show that these prices have reduced in recent years and are expected to reduce further to exceed cost of conventional energy sources)
- Today's processes run usually 24/7 for 10-12 month per year and are not compatible with large fluctuations of renewable electricity production. Changing to renewable sources however offers the opportunity of co-locating decentralized industrial production with decentralized production of sustainable electricity.

Furthermore, non-conventional energy sources, such as microwave, plasma, photons, ultrasound and laser (all examples of more direct energy transfer to the target molecule or material), have already been tested in process intensification at lab scale, showing significant improvements in the main process parameters (e.g. reaction selectivity/homogeneity, crystal nucleation, reaction speed) and in the overall energy efficiency (by bringing the right amount of energy on the right place in the subsequent processes upstream and downstream reaction). They are suitable for connection to the electricity grid and can significantly improve the productivity of industrial processes. They provide higher production flexibility, allowing variable throughputs to better follow market demand and enabling leaner production paradigms (e.g. decreased stock, production on demand), as well as flexibility for the electricity grid via demand response. Furthermore, such technologies are suitable for downscaling, which can be an advantage in some cases (e.g. in-situ biomass processing). They are well suited to continuous processing and can be conveniently coupled with real time monitoring and control systems. These processes can be developed for more tailor-made and local production. Local production can be an advantage in case local renewable feedstocks are used (e.g. waste or biomass).

In order to avoid process emissions, resulting from the chemical conversions in the different process industry sectors (e.g. cement, steel, chemicals, metals, etc.) carbon capture and use (CCU) will be used. These processes will make use of renewable energy (again extra need), green hydrogen, and several innovative processes that work at lower energy needs compared to the nowadays processes (as CO_2 is a quite inert product which need an high energy input or electron donor to be reduced). This CCU is part of this 'Systems' approach as it asks for strong integration between sectors and relies on new production methods with less CO_2 emissions output.

This CCU topic has some overlaps with Activity 5.5 on the use of steel mill gases as syngas for fuels and chemicals (special attention to gases from steel mills with conversion via syngas fermentation and chemical conversion of syngas to ammonia). The link with the cement industry is presented in Activity 3.3 with most of the attention to the capturing of CO_2 from cement kilns with applications in carbonatation and fuel production. The link to the chemical industry is via Activity 4.4 on CO_2/CO as alternative feedstock to chemistry (special attention to catalyst and reactor development).

In Systems, the focus lies on the integration of capturing, purification, conversion leading finally to end-products with lower CO_2-footprints compared to the original fossil-feedstock based production and taking into account the renewable energy needs for those processes.

However, further research and upscaling work is needed before deployment on an industrial scale.

Types of actions / projects needed include:

- Set up of pilot plants for process industry making use of non—conventional energy sources
- Linking of these energy sources to renewable electricity
- Linking these processes to carbon capture and use including the adaptation of the processes to simplify the carbon capture (e.g. by providing pure oxygen in the input and no air or by improving the process as such that it provides a higher CO_2 concentration in the flue gas).
- Comparison between innovative use and conventional use in the process
- System that pays attention to energy losses or efficiency (e.g. by converting non-conventional energy from processes or reactions into energy)

Finally, further solutions for value chain optimisation through addressing energy efficiency considerations in the design phase of manufacturing equipment and processes, collective demand side strategies, and potential integration of the nearby renewable energy sources should be also considered.

Impact:

- Increase potential for integration of the non-conventional energy technologies with renewable energy sources such as wind and photovoltaic, including management of fluctuations.
- Improvement in energy efficiency of 30-35% compared to the current state of the art process (or similar one). It can be calculated as energy savings compared to current operations.
- Decrease in GHG emissions by 25-30% or by a smaller percentage but significant absolute (tbd) amount (without considering the GHG emissions of electricity generation and at steady state) compared to the current state of the art process (or similar one).
- Decreased OPEX and CAPEX by 20% compared to the current state of the art process.
- Decrease of 30-50% of GHG emissions of the production process for fuels, chemicals, materials compared to nowadays conventional fossil-based production systems.

The above impacts might differ and depend on, for instance, the maturity of the equipment, the developments and breakthrough technologies deployed in the production sites. Sectors having smaller scale equipment might be able to achieve high relative (%) improvements, while a high absolute number would apply for sectors having large scale and already fairly optimised equipment.

The impacts are subject to the execution of the whole cycle of the long term program, including several projects from low TRL to high TRL.

Moreover, in addition to achieving large GHG emissions reductions excluding the electricity production, the impact in terms of GHG emissions reductions including the GHG emissions of electricity generation shall also be significantly positive. The GHG embedded in electricity depends on the localisation and the time horizon; the average for EU shall be considered: 265 gCO2eq/kWh in 2020, 181 gCO2eq/kWh in 2030 .

Primary energy saving potential: ktoe/a (assuming full deployment in the EU27)

GHG emission saving potential: ktCO2eq/a (assuming full deployment in the EU27)

To be provided at a later stage as it needs to be assessed further by the sectors. Current analysis is not yet consolidated.

Technology Readiness Level (TRL): The projects should start on low to medium TRL 4 levels mainly targeting research and demonstration of the proof of principle at small scale TRL6 or start at medium TRL 6 and go to the demonstration of in an industrial relevant environment (TRL9).

Due to the diversity of the different scenarios depending on the sectors, we encourage to cover from a low TRL as 4 while reaching up to TRL 9 in other sectors. Impacts also might vary depending on the TRL and sectors. Therefore, it is encouraged to consider the above impact figures as well as reduction of a significant amount of GHG at the evaluation phase.

Total budget required: €20–30m per project (TRL 4-6) and €10-20m per project (TRL 6-9).

- €200 m for electric furnaces and crackers each
- €50 m per CCU demonstration plant (TRL7-8)

Expected deliverables	*Fill in one line per deliverable* • *Preparation of several processes based on non-conventional energy use* • *Pilot plants operational at TRL 7-8* • *Demonstrations at TRL 8-9* *Calculations on energy efficiency and productivity including other savings*
Timeline	*36 – 60 Months / project recommended*

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
Industry, research centres, universities	• Funds at EU level should be guaranteed in order to achieve true cross-sectorial EU dimension of technologies development and demonstration (e.g. Horizon Europe, notably the Process4Planet partnership) • Other complementary funds or tools could cover specific territorial interests (e.g. national or regional funds) or support deployment (e.g. Investment and financial instruments from EIB, ETS Innovation Fund et al.) • Some regional/local funding will be needed in order to assure logistics for the interaction between CO_2 capture and CO_2 use partners.	*To be provided at a later stage*

Gaps:

- Pilot scale facilities need to be built. At the moment, most of the results are obtained in rather small to lab scale installations
- Processes need to be converted from batch into continuous and this needs a new way of monitoring as well
- These processes cannot be up scaled on existing plants and need new installations, meaning a high CAPEX-cost
- Efficient conversion of renewable energy into the new energy sources is still an issue
- A good LCA study will be necessary to show the additional savings (on top of the energy savings)

9.2.3 Activity 2.3 – Digitalisation: Further integration in process and plant management including plant/process design phase and processing plant retrofit

Title: Digitalisation: Further integration in process and plant management including plant/process design phase and processing plant retrofit		
TG: Systems	**Activity No: 2.3**	**Activity leader: A.SPIRE**
Targets: Process control and process automation solutions to enable small and large industries efficient plant design and operation leading to reduced energy consumption and GHG emissions.		**Action 6 monitoring activities will draw on relevant industry publications.** Level of development of deliverables

Description:
To reach a significant step forward on energy efficiency compared to today's industrial reality, new ways to improve flexibility in plants, optimise consumption and reduce GHG emissions are necessarily driven by digital technologies and process automation.

In order to drive continuous sustainable progress and innovation in the process industry, to effectively enable improved resource and energy efficiency, enriched process understanding and evaluation of the impact of each decision from early process/plant design phase to production management is essential.

Hence, process design, engineering methodologies and systems engineering methods and tools, such as process modelling, simulation and control strategies, are essential to support decision making as regard to all aspects including feedstock, energy management, production pathways, extrapolate and catalyse the dissemination of advanced process technologies, into all kinds of production units and optimize asset management and also explore industrial symbiosis between process industries sectors.

Linking process modelling capabilities with eco-efficiency and economic models is also a requirement for qualified, knowledge- based decision making for sustainable intensive industries production.

Sustainability evaluations require lots of data, expertise and effort. Consequently, these detailed analyses can often only be done at higher Technology Readiness Levels, by which point they are less able to influence the overall design decision systems. Bringing appropriate sustainability assessment at earlier stage of the process/product development (starting ~TRL 4) is therefore essential. A major breakthrough would be the availability of software platforms integrating sustainability advanced assessment tools, process and plant design tools, and databases, with simulation capabilities along the whole life-cycle of a plant and adapted to early design phases of processes and plants. It would support optimal product and process design, plant engineering, procurement, plant construction, commissioning, possible operation modifications, as well as plant flexibility, operation and maintenance campaigns, extensions and reuse for next generation and new products.

During plant operation, cognitive equipment and plants retrieving information from sensors for continuous and batch processes are essential to optimize production operations. This is linked with simulation capabilities including combined multi-scale and multi-physics first principle models and data analytics in high performance computing environment to enable cyber-physical systems for the online plant control and management. In this context, attention is focused on recognition of unusual situations, proposal of optimized recovery measures, condition monitoring and processing of environmental targets, energy consumptions, emissions, including retrofit of process industries 'brownfield' assets.

Furthermore, advanced data analytics would allow companies to convert various type of data (from R&I, engineering, production, asset management, marketing, sales, other production site, etc.) into knowledge in real-time, and effectively contribute to more sustainable manufacturing processes with more resource and energy efficiency on production sites and potentially between industrial sites

Excess heat recovery is following the "energy efficiency first" principle, available excess heat is used as source to supply the internal energy demand on process or supply level, or as an option integrated into grid-bases supply systems for nearby industry or District Heating (DH) networks. It is essential to follow a reliable methodology in order to identify the optimised system and integration possibility (e.g. source/sink combinations, storage depending on load profiles and simultaneities). The PINCH analysis is a feasible methodology, applying the criteria of exergy, heat exchanger capacity and saved energy of a heat exchanger network. Of high interest is the optimised combination of direct excess heat recovery with indirect use via heat pumps, well integrated in hybrid renewable supply systems (heat pump, PV, PVT, biomass, biogas and storages). The optimised design and operation of such systems, for both industry internal and external integration, requires the demand and supply system to be simulated based on component simulation models.

Digitalisation is the key for this approach, following the core objective of easy applicable approaches and solutions.

Specific developments (actions or projects) should therefore include:

1. New reliable hard and soft sensors to enable advanced inline process and product measurement systems as inputs model-based control of process and process chains.
2. Simulation capabilities along the whole life-cycle of a plant specifically in early design phases of processes and plants, use 'digital twins' as simulation tool.
3. Overcoming the modelling bottleneck, reduce the effort for modelling, improve model re-use, and develop strategies for model maintenance and adaptation, "living" models considering control, scheduling, planning and demand-side management.
4. Humans in the loop - what is the role of humans in the operation of plants in the process industries, how can their role and their knowledge and experience be optimally combined with advanced control algorithms and optimization, how can humans supervise complex computer-based solutions; this includes but is not restricted to human-machine interfaces Strategies to efficiently retrofit process automation in brownfield plant/side environments.
5. More resilience against cyber-attacks including identification and real-time counteracting.
6. Explore the possibilities of having a micro grid between industries, which includes distribution, consumption and storage of energy (conventional, alternative, renewable), as well as advanced monitoring, control and automation systems though IT systems (linked to fiche 5.1 and 6.2).
7. Sensing systems, digitally operated to manage new sustainable, less homogenous feedstocks, energy mixes and energy fluctuations.

Impact:

Advanced online monitoring is expected to play a key role to achieve significant energy efficiency improvement in the European process industry. Recent projects report energy efficiency improvement between 5-15%, but specific impact will actually depend on current level of energy efficiency of each site.

Advanced sustainability assessment tool and integration in process modelling/design tools supporting early decision making and digital engineering would enable improved design of new plants and optimized valorisation of existing assets (brownfield) to be re-designed with expected high GHG saving potential.

Improved capabilities for valid, reliable and real-time control logics of the properties and quality of process streams and final products for existing and for more flexible process operation concepts:

- Strengthening of the competitiveness of the European industry both in the domain of measurement technologies and control solutions and with respect to economically sustainable industrial processes
- Retention and creation of jobs for the European measurement and automation and process industries

Primary energy saving potential in percentage and in ktoe/a (assuming full deployment in the EU27)
GHG emission saving potential in percentage and in ktCO2eq/a (assuming full deployment in the EU27)

To be provided at a later stage as it needs to be assessed further by the process industry sectors. Current analysis is not yet consolidated

Technology Readiness Level (TRL): Advanced research and Industrial research & demonstration ; *TRL 4-5 to TRL 8*

Total budget required €20 million per project and > €50 million for projects at TRL8 recommended

Expected deliverables	Timeline

• Advanced sustainability assessment tool and integration in process modelling/design tools for decision making starting at TRL 4 (of process/product development phase) including connection to data platforms • Advanced energy and resource management control strategies integrated into process automation systems and plant operator's tasks • Software platforms for optimized digital engineering and plant design, re-design/upgrade and plant management • Cognitive equipment and plants systems including advanced process control and monitoring technologies and model-based control for optimized production automation. • Specification of electrical network of the companies involved • Conceptual Design/ Software Prototype of the network (Wireless-Transmission-System, system performance report, etc.) • System Integration and Validation Test Plan/ Report • Pilot preliminary evaluation	Projects of 36 to 48 months are recommended

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
• It might be beneficial to all EU countries. • In all cases, industrial sites and clusters are at the core of those initiatives as integration of IT systems could transform the way they operate thoroughly. • Industries with waste heat could be interested (for example, cement, glass ceramics, etc.)	• Funds at EU level should be guaranteed in order to achieve true cross-sectorial EU dimension of technologies development and demonstration (e.g. Horizon Europe, notably the Process4Planet partnership) • Other complementary funds or tools could cover specific territorial interests (e.g. national or regional funds) or support deployment (e.g. Investment and financial instruments from EIB, ETS Innovation Fund ...)	*To be developed at a later stage*

Gaps: Barriers or shortcomings that stand in the way of meeting the goal include:

- Lack of workforce educated to use digital technologies as central sources for process optimization, control, smart data applications and plant maintenance
- Need to improve standardization of software interfaces
- Need for efficient and safe use of cloud/data platforms/computing possibilities
- Need for advanced and reliable process analytics (e.g. cognitive-computing, data-utilization of high-performance computing (HPC)
- Need for methodologies to retrofit brownfield assets

9.2.4 Activity 2.4 - Knowledge exchange, training and capacity-building: Improving exchange of technological, economic, behavioural and social knowledge; training, capacity building and dissemination, to enhance sustainable energy management

<table>
<tr><th colspan="3">Title: Knowledge exchange, training and capacity-building: Improving exchange of technological, economic, behavioural and social knowledge; training, capacity building and dissemination, to enhance sustainable energy management</th></tr>
<tr><td>TG: Systems</td><td>Activity No: 2.4</td><td>Activity leader: European Platform of Universities in Energy Research and Education (EUA-EPUE)</td></tr>
<tr><td colspan="2">Targets:
In order to develop and demonstrate solutions enabling small and large industries to reduce their energy consumption by 20% while striving to reduce GHG emissions proportionally by 2025 we need to:
1) Build stakeholders with right technological, economic and social skills via training and capacity building to allow the planned sustainable energy management.
2) Obtain an industrial and social community fully aware of sustainable energy management needs for a future green Europe.</td><td>Action 6 monitoring activities will draw on relevant industry publications.

Possible primary data collection to monitor progress (not monitored under SET Plan)
1) Market stakeholders with increased multidisciplinary skills/capability/competencies (for example to be measured in number of people participating in trainings, workshops, mobility schemes)
2) Number of people/enterprises engaged in activities contributing to sustainable energy management culture documenting why and how changes are an effect of particular measures taken, as well as in terms of the sustainability of the behavioural change</td></tr>
</table>

Description:
In accordance with the principles of a circular economy, this R&I Activity should aim at increasing cooperation between major stakeholders (academia, industry, SMEs, authorities, research institutions, communities) in order to adopt a total industrial district approach opened also outside industrial plant perimeters (e.g. buildings, DHC, etc). All energy providers and users as well as major stakeholders should be involved in the process.

Mapping the methodological approaches and tools available in academia, research organisations and best practices from industry (the evaluation of energy efficiency methodological approaches and tools should also include carbon footprint impact). Mappings should be accessible to industry and should be disseminated to training providers in order to coordinate training efforts across Europe. These tools may be applied for example to diagnosis, evaluation and optimisation of energy efficiency of systems and processes. The possible actions proposed could be:

- Developing networks of pilot plant installations for highly advanced energy efficiency technologies. The objective is to generate optimal technology networks in order to utilise resources and transform them to useful products and energy services.

- Contributing to the development of innovative business and contracting models along the value chain, also facilitating actual implementation of energy cooperation between businesses and between universities, research organisations and businesses.

- Mapping the needs for future training at the level of academic, but also technical education. This will be based on business models, digital skills, communication skills, technical issues etc.

This would foster collaboration from lab to pilot scale and from pilot scale to industrial demonstration.

Improve the level of awareness and overall 'sustainable energy management culture' of industrial companies and SMEs (as indicated in SET-Plan Integrated Roadmap, Annex I, Part I Energy Efficiency, p61-2, `INNOVATIVE AND MARKET UPTAKE PROGRAMME`). This includes:

- Providing exchange of knowledge between universities, research organisations and industry, including training to industry on how to best use methodological approaches and tools available in academia and research organisations.

- Providing training and capacity building programmes to industry staff at all levels towards the promotion and implementation of an energy efficiency culture in industry. A clear participation of both managerial and operational staff must be ensured.
- Awareness raising of citizens via innovative communication tools (e.g. citizen science projects).

This objective should duly take into account the impact of policy measures in improving the energy culture of industrial companies and SMEs.

Impact:

- **Market stakeholders with increased multidisciplinary skills/capability/competencies (**for example to be measured in number of people participating in trainings, workshops, mobility schemes etc.)
- **Number of people/enterprises engaged in activities contributing to enhanced sustainable energy management culture** documenting why and how changes are an effect of particular measures taken, as well as in terms of the sustainability of the behavioural change
- **Indirect impact:**
- **Primary energy savings triggered by the project (GWh/year)** per million Euro of project funding
- **GHG emission savings triggered by the project (ktCO2e/year)** per million Euro of project funding

Technology Readiness Level (TRL):
TRL at start: 5 (Methods, technologies and pilot plants are already available); TRL at the end: 7 (The tools and methods shall be utilised in industrial practice and design). Start TRLs below 5 should be considered in the case of start-ups, spin-offs or innovative businesses at early stages of their creation and development. Concerning training and capacity building activities, the TRL at the end would be level 9.

Total budget required between €1 and 2 million per project/deliverable.

Expected deliverables	Timeline
1. **Maps** related to energy efficiency in industry as detailed below.[59] a. Mapping of a "network of pilot plant installations" in universities, other research organisations and industry. The mapping of pilot plant installations must be accompanied by the development of innovative business models on how to jointly utilise such installations to reduce time to market. It should include also innovative business and contracting models contributing to increase energy cooperation between businesses with a view to better industrial symbiosis. In order to assure the continuation of these networks it can be an idea to get them supported by the Member States. b. Mapping of existing business and contracting models as explained in deliverable 3. This would create synergies with the previous point on mapping of pilot plant installations. c. Mapping of methods: analytical methods and simulations aiming at improving value chain optimisation ('total industrial district' integration as well as industrial symbiosis and symbiosis between industry and buildings, in the wider context of a circular economy). For all these approaches there are numerous methods available in universities, research centres, companies and other stakeholders. The European Community of Practice, supported by Processes4Planet, can play a strong role in these mapping of methods, but also of available energy flows and technologies spread over the different Hubs4Circularity over the regions in Europe. 2. **Dissemination activities and training courses on energy and resource efficiency:** Training in analysis methods and value chain optimisation methods for energy and	*Project Month (start = project Month 0)*

[59] For example, to be added to the collection of maps in the European Atlas of Universities in Energy Research & Education, available at: http://uni-set.eu/index.php/atlas/. The Atlas includes (among other data) relevant information of master, doctorate and research programmes in the field of energy efficiency.

resource efficiency. These training and dissemination activities can be targeted towards SME and larger industry, helping the transfer of new technology and scientific knowledge generated by universities and research centres to business or from businesses to businesses. Cross-border collaboration among industries should be fostered and peer-to-peer exchange should be facilitated. The expected results would be an improved energy culture of industrial companies and SMEs towards energy efficiency. A map of educational professional training bodies should facilitate this task.

3. **Analysis of existing business and contracting models and proposals for new business and contracting models, taking into account organisational, financial, legislative, social and technological barriers.** This activity would contribute to increase energy cooperation between businesses in view of industrial symbiosis under the principles of a circular economy. Similar to deliverable 1 and 2, existing business models including especially the innovative ones should be mapped. Based on those, innovative models should be proposed, in cooperation with also the energy regulators.
4. **Guidelines on multidisciplinary approaches** in higher education and research programmes (particularly in Master, Doctorate and Research Programmes) for industrial processes and development of innovative business models. These guidelines should become a reference point for the upgrade of existing programmes or the generation of new ones.

Parties/Partners (countries/stakeholders/EU)	**Implementation financing/funding instruments**	**Indicative financing contribution**
Stakeholders: academia, industry, research institutions, financial institutions, local and national authorities, communities	A mixture of national, European and private funding	between €1 and 2 million per project

Gaps: Lack of awareness; lack of knowledge; lack of tools.

9.3 Cement Activity Fiches

TO NOTE: Due to competition laws, project-specific and some general information **cannot** be provided.

9.3.1 Activity 3.1 – Resource efficiency

Title: Resource efficiency / Circular economy - Alternative fuel use		
TG: Cement	**Activity No: 3.1a**	**Activity leader: CEMBUREAU**
Targets: Short-term: Increase share of alternative fuel use to 60% by 2030 Long-term: Increase share of alternative fuel use to 95% by 2050		**Action 6 monitoring activities will draw on relevant industry publications.** E.g. Regular update of CEMBUREAU Roadmap

Description:
Using alternative fuels substitutes fossil fuels (oil, petcoke) as primary raw materials in heating the kiln with secondary fuels taken from a variety of waste streams, including biomass waste. Approximately one third of cement manufacturing emissions are combustion emissions and come from the fuels used to heat the kiln.

Impact:
Use of alternative fuels puts the cement industry at the heart of the circular economy and of waste management as it uses non-recyclable waste as a fuel or as an alternative raw material. To date, the cement industry substitutes 48% of its primary fuels through secondary alternative fuels (gradually increasing from 2% in 1990). Achieving a 60% alternative fuel use would result in an avoidance of 26 million tonnes of CO_2 emissions annually and a saving of 11.1 million tonnes of fossil fuels.

Gaps:
There are no technical impediments to increase the use of alternative fuels in cement kilns. The main barriers are regulatory in nature and vary amongst Member States (lack of landfill ban; permitting issues; taxation). CEMBUREAU has carried out two studies with Ecofys (link to studies).

Title: Clinker substitution and concrete recycling - Activated clay and other materials for clinker replacement. Conversion of by-products into performance-building products.		
TG: Cement	**Activity No: 3.1b**	**Activity leader: CEMBUREAU**
Targets: Short-term: Reduce clinker to cement ratio to 70% by 2030 Long-term: Reduce clinker to cement ratio to 65% by 2050.		**Action 6 monitoring activities will draw on relevant industry publications.** Regular update of CEMBUREAU Roadmap

Description:
Clinker production is the most CO_2 intensive part of cement production. Replacing clinker with alternative materials can therefore reduce CO_2. Availability of slag (from steel blast furnace) and fly ash (from power stations) will diminish with the decarbonization of the steel and power sector so the cement industry needs to investigate further alternatives such as activated clay. In addition, there is ongoing research and testing on recycling aggregates from concrete demolition waste with a view to using it to produce new concrete. The IRCOW project is a good example of ongoing research in the area.

As the largest source of CO_2 comes from the process emissions (i.e. from calcining the raw materials in the kiln) innovation and research should focus on:

- Studies to determine potential sources of alternative waste raw materials, including how waste materials and by-products from other industries can be used to replace some of the limestone, in an industrial symbiosis approach;
- Research into new types of cement clinkers with less limestone in the formulation (sulpho-aluminate clinker, ferro-aluminate clinker, belite ye-elimite-Ferrite Clinker, amorphous clinker). As these cements have different properties from conventional Portland cement clinker, they can only be used for specific applications and, once developed, their market share is estimated around 5% and they will continue to be a niche market;
- Research into reducing the clinker content in cement which comprises research into non-traditional substitutes such as calcined clay, silica, pozzolan materials from waste streams and slag from other industries.

9.3.2 Activity 3.2 – Energy efficiency

Title: Improved thermal efficiency - Kiln conversion and waste heat recovery		
TG: Cement	**Activity No: 3.2a**	**Activity leader: CEMBUREAU**
Targets: **Short-term:** 4% improvement in thermal efficiency by 2030 **Long-term:** 14% improvement in thermal efficiency by 2050		**Action 6 monitoring activities will draw on relevant industry publications.** E.g. Regular update of CEMBUREAU Roadmap

Description:
Cement kilns are already efficient, typically operating at levels between 70 to 80% efficiency. However, improvements can still be made to the thermal efficiency of some of our kilns through converting preheater and other kiln types to precalciner kilns and by recovering heat from the cooler to generate up to 20% of electricity needs for the cement plant.

Impact:
4% improvement in thermal efficiency by 2030. Recovery of heat from the cooler can generate up to 20% of electricity needs for the cement plant.

Title: Leverage thermal mass properties of concrete in buildings		
TG: Cement	**Activity No: 3.2b**	**Activity leader: CEMBUREAU**
Targets: **Short-term:** Cut energy-use by 25% to 50% in buildings during peak demand periods		**Action 6 monitoring activities will draw on relevant industry publications.** Regular update of CEMBUREAU Roadmap **Possible primary data collection to monitor progress (not monitored under SET Plan)** To be taken up with downstream construction operators/building companies

Description:
Currently 72% of CO_2 total emissions related to an average building, come from the energy used during its working life. A so far untapped benefit is to use the thermal storage capacity offered by the structure of a building to provide flexibility in energy grids and boost the uptake of renewable energy. Heavyweight buildings can provide this flexibility by allowing for consumer energy demand to be shifted in time ("active demand response") by using thermal energy storage.

Buildings that leverage the thermal mass properties of concrete, which also has a unique energy storage capacity, can cut energy use by 25% and up to 50% during the peak demand periods. Examples include a multi-story social housing project (Mühlgrundgasse, Vienna), residential passive house building (Lärkträdet, Vara, Sweden) and a multi-story office in Amsterdam. The multi-story building of the Technical University of Vienna (TUV) has a positive energy footprint by using thermal mass and solar panels. Thermal mass can also be incorporated into re-use of buildings where thermal mass is added to the concrete structure being refurbished for a new building use.

In conclusion, the revision of the Energy Performance in Buildings Directive needs to seize the opportunity to look at buildings as active participants in the energy system and as feeding into the grid rather than as passive energy uptakers.[60]

Impact: Energy use in buildings can be cut by 25% to 50%. Reduced transmission and distribution infrastructure, lower investment costs, lower operational cost for consumers (reduction €300/year per household), higher renewable energy penetration and reduced CO_2 emissions.

[60] See specific policy recommendations on p. 23-24 of the E3G study on structural thermal energy storage in heavyweight buildings http://www.theconcreteinitiative.eu/images/Newsroom/Publications/small_-_3E_StructuralThermalEnergyStorageHeavyWeightBuildings_2016-10-25_Light.pdf

9.3.3 Activity 3.3 – CCS/CCU in Cement sector

<table>
<tr><th colspan="3">Title: CCS/CCS in Cement sector - Capturing CO2 from the cement kilns</th></tr>
<tr><td>TG: Cement</td><td>Activity No: 3.3</td><td>Activity leader: CEMBUREAU</td></tr>
<tr><td colspan="2">Targets:
Short term: Pilot/demonstrators by 2030
Long term: Commercialisation 2030-2050; Carbon neutral along the cement-concrete value chain by 2050 ; 42% CO₂ reduction by 2050 if successful implementation of carbon capture technologies</td><td>Action 6 monitoring activities will draw on relevant industry publications. E.g. Regular update of CEMBUREAU Roadmap
Possible primary data collection to monitor progress (not monitored under SET Plan) To be taken up with downstream construction operators/building companies</td></tr>
</table>

Description:
Two thirds of the CO_2 emissions from cement manufacturing relate to the decalcination of limestone at a temperature of 1500° C / 1600° C in the kiln. This is a chemical process whereby CO_2 is released. CCS/CCU contributes to CO_2 reduction in the cement industry in the following ways:

Capture technologies - The cement industry has focused on a variety of CO_2 capture technologies with research undertaken at pilot scale to optimise reagent and membrane capture technologies. Trials are underway to find ways of concentrating the CO2 to make carbon capture more efficient and cost-effective. Below is a list of projects for which public information is available:

- Brevik project in Norway (HeidelbergCement) https://www.heidelbergcement.com/en/carbon-capture-and-storage-ccs Northern lights
- The Westküste 100 project which joins up several industries and applies the oxyfuel combustion and CO_2 capture at the Lagerdorf Zementwerke (LafargeHolcim) to create green methanol https://www.westkueste100.de/en/
- LEILAC I and II (II just started with a demonstration capture plant at the HeidelbergCement facility in Hannover); cement companies involved are HeidelbergCement, CEMEX, CIMPOR and (in Phase I) Tarmac (CRH). https://www.project-leilac.eu/
- Cleanker project which uses oxyfuel combustion and CO2 recycling to produce a CO2 gas stream of over 90% The demonstration plant is at a BuzziUnicem facility in Vernasca (Italy) http://www.cleanker.eu/
- Under the "Catch4Climate" initiative, launched on 18 November 2020, BuzziUnicem, HeidelbergCement, Vica and DSchwenk signed a LOI for a project aimed at creating a pre-industrial scale demonstrator of oxyfuel technology at the Schwenk cement plant in Mergelstetten, Germany.
- LafargeHolcim carbon capture project in Carboneras (Spain) / captured CO_2 will be used for agricultural purposes https://www.cemnet.com/News/story/169790/lafargeholcim-to-build-first-cc-facility-at-carboneras-plant.html

Storage - Captured CO_2 can be stored in geological formations where it is permanently stored. It is crucial for a successful deployment of these technologies that pipelines and storage sites are identified and built and this requires a joint effort of the European Commission, Member States and industry.

Other permanent CO_2 capture techniques include the use of recycled concrete aggregates and minerals (such as olivine and basalt). By way of example, the Dutch concrete recycling company Rewinn B.V., Amsterdam, which HeidelbergCement established together with its local partner Theo Pouw BV, Utrecht, Netherlands, is in a position to produce up to 250,000 tonnes of aggregates from recycled concrete per year. These are already used in numerous applications, such as the production of fresh concrete. Algae can also be used to absorb CO_2 and grow biomass, which can later be used to fuel the kiln. Under the Green Sky Project, CEMEX proposes to capture and utilize CO_2 from industrial flue gas produced during cement production by efficiently converting it into high-value products based on or derived from microalgae biomass, ranging from organic chemicals to nutritional additives like basic nutrients, omega-3's and others.

CO_2 conversion to products - Projects are underway in the cement industry whereby captured CO_2 is used to create new products such as carbon neutral aviation fuel. Several technologies (calcium looping, oxyfuel, post-combustion) are being tested now in pilot and demonstration projects.

Impact:
Potential 42% CO_2 reduction from a variety of carbon capture technologies by 2050.

Gaps: Not included.

9.3.4 Activity 3.4 – Recarbonation and mineralisation

Title: Recarbonation and mineralisation (Enhanced recarbonation of recycled concrete)		
TG: Cement	**Activity No: 3.4**	**Activity leader: CEMBUREAU**
Targets: **Long-term** Up to 8% saving in total CO_2 emissions for cement manufactured (assuming 23% of process emissions of cement used are captured annually)		**Action 6 monitoring activities will draw on relevant industry publications.** E.g. Regular update of CEMBUREAU Roadmap **Possible primary data collection to monitor progress (not monitored under SET Plan)**

Description:
Recarbonation is the process whereby concrete re-absorbs some of the CO_2 that was released during clinker production. In the built environment, recarbonation (absorption of CO_2) occurs naturally in all concrete infrastructure. Recarbonation especially increases after demolition of a concrete building. The recycled concrete aggregates have a higher surface area and can absorb CO_2 more easily within the concrete paste (cement, water and sand) from the ambient air.

Natural minerals such as olive or basalt when crushed can also be recarbonated when exposed to air or kiln exhaust gases. Once carbonated these materials can be used as clinker substitutes.

Impact:
Initial research has shown that recarbonation can be accelerated by using the exhaust gases from a cement kiln which have a higher CO_2 content and are at a higher temperature, increasing the CO_2 captured by up to 50% of process CO_2 emissions.

In order for recarbonation to be recognized in CO_2 reduction efforts, it needs to be recognised as such in the IPPC and European standards and regulations.

9.4 Chemical Activity Fiches

Some fiche information is not available at point of publication, therefore chemicals fiches presented here often do not include information in some Fiche fields (e.g. on the total budget required, Expected deliverables, Timeline, Parties / Partners, Implementation financing / funding instruments, Indicative financing contribution)

9.4.1 Activity 4.1 – Electrification

Title: Direct and indirect electrification of chemical processes		
TG: Chemicals	**Activity No: 4.1**	**Activity leader: Cefic**
Targets: While this fiche includes a portfolio of technologies that are currently at various TRLs, the overall technological development targets are defined as follows: **Short-term** (2030)**:** Demonstration projects to be launched by 2030. **Long-term** (2050)**:** Deployment of new technologies between 2030 and 2050.		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)**

Description:
Access to cost competitive climate-neutral electricity is an opportunity for the chemical industry to reduce its carbon footprint. Electricity can be introduced directly or indirectly in chemical processes.

<u>Indirect use of electricity</u> can be considered for heat[61] and steam generation or upgrade:

- Electric heating at high temperature (e.g. e-furnace, e-cracker).
- Electric heating at low temperature.
- Electricity based steam generation.
- Mechanical vapor recompression system to upgrade residual steam.

<u>Direct utilisation of electricity</u> via electrochemistry and use of unconventional energy sources.

Novel electrochemical processes can enable new reactivities that enable molecular transformations difficult to realise via thermochemical methods. Novel process technologies for electrochemical processes can provide new production routes for various chemicals, including through the valorisation of alternative carbon sources, including waste and CO_2. Electrochemical processes can also contribute to a more circular economy through separation of metals in waste streams, as well as catalyst recovery. Further utilisation of electrochemical processes for the production for chemicals would require the development of new catalysts, electrodes and compact electrolysis cells.
Alternative energy forms such as ultrasound, microwave, plasma, light are non-conventional, non-contact energy sources that create the possibility for new and flexible process windows in flow reactors. Energy sourced from non-conventional energy forms is efficient in terms of being applied exactly where it is needed, as well as reducing reactions times.

Expected Impact:
Energy supply in the European chemical industry is currently mostly based on fossil resources, and GHG emissions from combustion were evaluated at 67.7 $MtCO_2eq$ in 2018 (source EEA). The impact of power-to-heat technologies is therefore very high if access to climate neutral electricity is economically viable.
As they offer opportunities for direct utilisation of climate neutral energy in chemical processes, the contribution of electrochemical processes and alternative energy forms to reduce the environmental impact of chemical processes can be high as they can also contribute to the utilisation of alternative carbon feedstock (quantitative impact specific to each target molecule and process).

[61] *Note: Heat pumps are addressed in the Heating & cooling section*

TRL: Technology development is needed for high temperature heating, in particular e-cracker technologies with the objective to reach TRL 8 by 2030.
Promising electrochemical processes currently at TRL 5-6 to reach TRL 8 by 2030
Intensified processes using unconventional energy forms to be demonstrated by 2030

Gaps:
Non-technical priorities include:

- Access to climate neutral electricity at competitive price.
- Risk-sharing measures through appropriate financial instruments for demonstration plants and first-of-its-kind plants.

9.4.2 Activity 4.2 - Integrated production of Hydrogen with low carbon footprint

Title: Integrated production of Hydrogen with low carbon footprint		
TG: Chemicals	**Activity No: 4.2**	**Activity leader: Cefic**
Targets: While this fiche includes a portfolio of technologies that are currently at various TRLs, the overall technological development targets are defined as follows: **Short-term** (2030)**:** Demonstration projects to be launched by 2030. **Long-term** (2050)**:** Deployment of new technologies between 2030 and 2050.		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)**

Description:
Hydrogen is an essential element of most chemicals. Therefore, the chemical industry is both a major producer and consumer of hydrogen. Currently hydrogen is almost exclusively produced by SMR in the chemical industry, but it also occurs as by-product in steam cracking, propane de-hydrogenation (PDH) and chlor-alkali electrolysis.
As the production of hydrogen with a low environmental footprint at competitive cost is key to reduce emissions in the chemical sector, in addition to water electrolysis, technologies such as methane pyrolysis or photoelectrocatalysis are under development for cost competitive production of hydrogen, and some bio-based routes are also explored.
Methane pyrolysis results in the production of hydrogen and solid carbon with less electricity requirement compared to water electrolysis technologies. The utilisation of climate neutral electricity can enable the production of low CO_2 emissions hydrogen at industrial scale from various sources of methane including biomethane or methane by-product from e-crackers.
Photoelectrocatalysis (PEC) allows converting solar energy into chemical energy in a single process, enabling direct production of hydrogen from water splitting without external electricity input. PEC cells can operate at ambient pressure and temperature with high energy efficiency.

Technical priorities include optimisation of:
- Reactor design.
- Photocatalyst and photoelectrodes for PEC.
- Efficient heating concepts for methane pyrolysis.

Impact:
Reduction of GHG emission estimated to be above 90% vs SMR production.

Technical Readiness Level (TRL):
Methane pyrolysis: from TRL 4-5 to TRL 9 by 2035. Photo-electrocatalysis: from 2-4 to TRL 8-9 by 2035.

Gaps:
Non-technical gaps include:
- Policy framework.
- Risk-sharing measures through appropriate financial instruments for demonstration plants and first-of-its-kind plants.
- Cost competitive access to climate neutral electricity for methane pyrolysis.

9.4.3 Activity 4.3 - Plastic waste as an alternative feedstock

Title: Plastic waste as an alternative feedstock		
TG: Chemicals	**Activity No: 4.3**	**Activity leader: Cefic**
Targets: While this fiche includes a portfolio of technologies that are currently at various TRLs, the overall technological development targets are defined as follows: **Short-term** (2030)**:** Demonstration projects to be launched by 2030. **Long-term** (2050)**:** Deployment of new technologies between 2030 and 2050.		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)**

Description:
Innovative process technologies can enable the utilisation of plastic waste for the production of chemicals and polymers in the chemical industry. To meet the ambitious European objectives, much more waste plastic needs to be recycled and a broader range of markets need to be served with plastic products containing recycled content. Chemical recycling technologies break down plastics and transform them into valuable secondary raw materials to produce new chemicals and plastics with the same quality as those made from fossil resources. Chemical recycling complements existing mechanical recycling to recycle mixed or contaminated plastic waste that otherwise would be incinerated or sent to landfill.
Different types of chemical processes can be used to recycle plastic waste:

- Pyrolysis and gasification for conversion of mixed plastic waste to (oil or gas) feedstock. The conversion takes place in a reactor in the absence of oxygen (pyrolysis) or presence of oxygen (gasification). In a following step, potential contaminants are isolated and removed. The produced oil or gaseous feedstock (re)enters the chemical production chain at the refinery or cracker level as secondary raw material replacing newly extracted fossil feedstock.
- Depolymerisation process – often referred to as chemolysis or solvolysis – uses different combinations of chemistry, solvents and heat to break down sorted polymers into monomers.
- Dissolution: sorted plastic waste is dissolved to extract the polymer.

Major priorities for technical development include:

- Operability including robustness allowing use of a wider range of plastics mixtures, process yield, and addressing reactor fouling for gasification and pyrolysis.
- Removal of impurities.
- Critical pre-treatment for depolymerisation.
- Batch to continuous processes for depolymerisation.
- Integration into existing chemical plant operations, either as feedstock or as monomer.
- Downstream separation and purification for depolymerisation.

Impact:
Implementing chemical recycling technologies at scale in Europe, can:

- Increase resource efficiency, reduce the use of fossil feedstock to produce plastics, and help to close the loop in the transition to a circular economy for plastics.
- Contribute to GHG emission reduction. Chemical recycling can eliminate the emissions associated with incineration and conventional production of feedstock materials.

Quantitative impact depends on the specific technology/polymer.

Technical Readiness Level (TRL):
Technologies are currently at TRL 4-8 depending on the technology (and depending on the polymer for depolymerisation and dissolution routes).

Gaps: Beyond the development, scale-up of technologies and business plans for recycling of plastic waste by the chemical industry, major challenges to be addressed include:

- Integration into existing chemical plant operations including purification, either as feedstock or as monomer.
- Access to feedstock with consistency of plastic waste input quality from the collection and sorting processes.
- Enabling regulatory framework for the development of the business case for chemical recycling of plastic waste.

Chemical recycling forms an integral part of the plans of the Circular Plastics Alliance (CPA)[62] and European Plastics Pact[63] that aim at addressing the above-mentioned gaps.

[62] https://ec.europa.eu/growth/industry/policy/circular-plastics-alliance_en
[63] https://europeanplasticspact.org/

9.4.4 Activity 4.4 - CO_2 / CO as an alternative feedstock

Title: CO_2 / CO as an alternative feedstock		
TG: Chemicals	**Activity No: 4.4**	**Activity leader: Cefic**
Targets: While this fiche includes a portfolio of technologies that are currently at various TRLs, the overall technological development targets are defined as follows: **Short-term** (2030)**:** Demonstration projects to be launched by 2030. **Long-term** (2050)**:** Deployment of new technologies between 2030 and 2050.		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)**

Description:
The utilisation of CO_2 (and CO from 'industrial waste gases') as alternative feedstock is one of the options that can be considered by the chemical industry to reduce the environmental footprint of chemicals and polymers. A broad portfolio of technologies can be used to use CO_2 as feedstock including:

- Power-to-X technologies in particular for the production of syngas, methanol.
- Direct electrocatalysis to C_1 and C_{n+1} molecules.
- Biotechnology routes to C_1 and C_{n+1} molecules.
- Direct utilisation of CO_2 for the production of C_{n+1} molecules through thermocatalytic routes.
- Direct utilisation of CO_2 for the production of polymers through thermocatalytic routes.
- Direct utilisation of sunlight through photo(electro)catalytic systems.

Major priorities for technical development include for the conversion step:

- Catalyst design as catalyst plays an essential role in the chemical valorisation of CO_2 which has a very low energy content and low reactivity. Objectives are to develop catalysts:
  - With high efficiency and selectivity given the low reactivity of CO_2;
  - Less prone to poisoning enabling the utilisation of less purified CO_2 streams;
  - Enabling CO_2 valorisation processes at lower temperature and/or pressure;
  - For direct CO_2-to-chemicals including one step conversion for CO_2 to C_{n+1} and CO_2 to polymers;
  - For direct CO_2 electrochemical and photo-electrochemical reduction reactions;
  - Based on abundant metals.
- Optimization of reactor concepts, design and engineering for thermocatalytic, electrocatalytic, photo(electro)catalytic, biotech conversion routes.

In addition, efficient capture and purification of CO_2 (as well as CO from off gases) streams from various sources (see also efficient separation technologies – Activity 4.6) are essential to improve energy efficiency and cost and enable subsequent, well performing CO_2 (and CO) valorisation reaction.

Impact:
The chemical valorisation of CO_2 has the potential to contribute to:

- Circular economy and resource efficiency and reduction of Europe's dependence on imports of fossil resources.
- GHG emission reduction: quantitative impact depends on the target molecule and technological pathway.

Technical Readiness Level (TRL):
Technologies are at TRL 2-8 depending on the technology and target molecule.
A few technologies are at TRL 8 (e.g. methanol, polyol).
Many technologies currently at TRL 4-7 have the potential to reach TRL 8/9 by 2030.

Gaps:
Non-technical gaps include higher production cost vs conventional fossil-based production, and the need to provide:

- Competitive access to climate-neutral electricity for electricity-driven electrochemical processes.
- Dedicated guidelines enabling a common understanding of how to evaluate the environmental impacts of CO_2 valorisation technologies.
- An appropriate policy framework ensuring that existing and future policies adequately recognise CO_2 valorisation technologies taking into account the abovementioned guidelines.
- The recognition in the Emissions Trading System (ETS) Monitoring and Reporting Regulation (MRR) (and any future regulation in this area) based on carbon accounting principle of CO_2 emission avoidance resulting from the utilisation of CO_2 as alternative carbon feedstock.
- Risk-sharing measures through appropriate financial instruments for demonstration plants and first-of-its-kind plants. Appropriate funding for technology development along the value chains at all Technology Readiness Levels (TRLs) in Europe at EU and national level.

9.4.5 Activity 4.5 - Biomass as an alternative feedstock

Title: Biomass as an alternative feedstock		
TG: Chemicals and Pulp & Paper	**Activity No: 4.5 (& 6.6)**	**Activity leader: Cefic and Cepi**
Targets: While this fiche includes a portfolio of technologies that are currently at various TRLs, the overall technological development targets are defined as follows: **Short-term** (2030)**:** Demonstration projects to be launched by 2030. **Long-term** (2050)**:** Deployment of new technologies between 2030 and 2050.		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)**

Description:
The utilisation of biomass is one of the options that can be considered by the chemical industry to reduce the environmental footprint of chemicals and polymers. Various types of biomass can be considered for the production of chemicals and polymers (e.g. sugars, vegetable oils, residues, agricultural or forest-based lignocellulosic biomass).
The pulp and paper sector has been increasing their product portfolio and create new markets for renewable, low-carbon products. This includes new functional cellulose-based applications and high value products from residual and side streams (e.g. lignin, hemicellulose and terpenes). Manufacturing of such products significantly improves resource efficiency.
The value chains towards biobased chemicals and materials include a large portfolio of technologies roughly categorised in pre-treatment, conversion and downstream processing. These technologies allow for the processing of a broad range of biomass feedstock into an array of high value products. The challenge is to link all processing steps into an integrated ecosystem to ensure that the production is resource, energy and cost-efficient.
Technological development is needed across all processing stages of biomass transformation into bio-based products.

<u>For the pre-treatment stage</u>, aiming to efficiently prepare biomass for the conversion process:

- Increase flexibility in the use of variable feedstock quality, maintaining as much as possible contained functionalities
- Increase efficiency of lignocellulose breakdown to all high-quality parts of lignin, hemicellulose, cellulose and inorganic parts, including the ability to process individual components of biomass without degrading other components
- Reduce the overall environmental footprint (energy and water needs) and integrate process intensification with lower capex and opex; evaluate the use of high-temperature electrical processes
- Develop and integrate adequate digital technologies for all the above.

<u>For the conversion stage</u>, aiming to convert pre-treated feedstock into bio-based chemicals and materials:

- Based on (thermo)chemical processes. They will be upscaled to achieve stable intermediate/product quality with higher resource and cost efficiency, integrating these processes and technologies into existing and new value circles and facilities.
- Based on chemical catalysis. They will deal more with oxygen-rich biomass (moving from a 'hydrocarbon-based petrochemical approach' to 'oxygen-rich biomass-derived feedstock approach'), developing new catalysts for reactive biomass and effective performance in aqueous environments, dealing with impurities and complexity/variety of biomass feedstock and developing new reactor technologies applying thorough knowledge of the kinetics of biomass-based reactions and catalyst deactivation.
- Based on biotechnology. Further developing the processing of fermentation both for bio-based chemicals, reducing yield losses and energy consumption, dealing with specific impurities and developing innovative enzyme cocktails to convert lignocellulosic biomass; increase the use of new technologies in microbiology and metagenomics, systems biology and synthetic biology for better biomass conversion and develop new bioreactors and new water management systems. Further developments of enzymatic catalysis and application of microorganisms, including extremophilic

microorganisms and extremophilic enzymes, including the use of omics and other techniques to identify, isolate and analyse microorganisms, potentially leading to new systems to obtain value-added products through fermentation. These also include metabolic engineering or any other advanced, new biotechnology to further improve the performance of microorganisms, in a safe working environment and manufacturing products and services that meet customers demand and requirements for consumers' safety.

- Develop and integrate adequate digital technologies for all the above.

For the downstream processing stage, aiming to recover, separate and purify the intermediate product from biomass conversion:
The conversion results (yields; purity or presence of impurities, contaminants or inhibitors; composition; etc.) will dictate the type(s) and emphasis of these stages. These could be single or combined applications of technologies for recovery, separation and purification of the targeted intermediates/products, with the following challenges:

- Further develop and upscale the product recovery from aqueous solutions, obtaining water of good quality to enable its reuse and/or developing processes and organisms that require minimal or no water, improving energy efficiency together with end product concentration and quality.
- Develop advanced selective purification techniques for high-value products or in-situ product recovery
- Develop and scale up robust filtration technologies for large volumes, resolving the issues related to plugging and contaminants,
- develop and integrate adequate digital technologies for all the above.
- Develop and use the existing infrastructures for upscaling and testing from applied research to commercial level,
- Develop industrial symbiosis to benefit from mutual product, side streams, residual streams and utilities opportunities.

In addition, setting up processing steps in a cascading mode to use the biomass feedstock and intermediate streams smartly and efficiently will lead to higher sustainability and economic competitiveness.

Impact:
The development of these new technologies within the chemical bio-based industry will increase resource- and energy-efficiency in each of the above stages of pre-treatment, conversion and downstream.

The quantitative impact is specific to each target molecule and process route.

Technology Readiness Level (TRL):
Technologies for the utilisation of biomass as feedstock in the chemical industry are at TRL 2-8 depending on the biomass, technology and target molecule.
Technologies at lower TRLs should be moved to pilot scale level (TRL 6 - 7) and technologies at medium TRL should be moved to demonstration plant (TRL 8) by 2030.

Gaps:
Non-technical gaps include:

- Increase and diversify sustainable feedstock availability for the production of chemicals and materials.
- Improvement of the biomass supply systems and management (logistics) by extending or improving existing systems, and/or design new innovative supply systems to facilitate/increase biomass feedstock supply for the production of chemicals and materials.
- An appropriate policy framework ensuring that existing and future policies adequately recognise the resource efficiency and GHG emissions benefits - along the value chain - of bio-based production and adequately stimulate investment along the whole value chain. The current framework (including PEF) does not incentivise investment in innovative processes enabling CO_2 emissions reduction in other sectors of the bio-based value chain. Methodologies for GHG emissions evaluation should stimulate investment in innovative technologies along the whole value chain of bio-based products.
- Risk-sharing measures through appropriate financial instruments for demonstration plants and first-of-its-kind plants.

9.4.6 Activity 4.6 - Process efficiency

Title: Process efficiency		
TG: Chemicals	**Activity No: 4.6**	**Activity leader: Cefic**
Targets: While this fiche includes a portfolio of technologies that are currently at various TRLs, the overall technological development targets are defined as follows: **Short-term** (2030)**:** Demonstration projects to be launched by 2030. **Long-term** (2050)**:** Deployment of new technologies between 2030 and 2050.		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)**

Description:
Process intensification, including **reactor design** concepts and equipment as well as new **catalysts** development can provide major opportunities for resource and energy efficiency as chemical reactions can be achieved at optimal conditions with significantly less side reactions creating fewer by-products, and using less auxiliary materials. As catalysts are key enablers for higher selectivity and reduced energy consumption, novel catalysts have to be designed to accommodate more complex and/ or variable feedstock quality (e.g. biomass, waste, CO2).
The introduction and further penetration of process intensification technologies can also achieve faster and more flexible modular and standardised chemical production including multipurpose plants.
Relevant developments include reactor concepts and equipment with optimisation of separation, reaction and heat and the integration of membranes and sorbents in reactors.
Process efficiency can be complemented at plant and site level with the implementation of other optimisation measures such as energy recovery technologies including from low temperature energy streams which still require R&I activities to increase their performance and reduce their cost.

Separation technologies are of crucial importance for large scale chemical and biotech processes, as they are essential in chemical processes for the purification of the products, recycling of solvents or catalysts, further valorization of by-products or gaseous effluents, removal of harmful substances etc. as well as access/pretreatment of alternative feedstock such as biomass and CO_2.
Most mature separation technologies are energy intensive, and separation operations can represent up to 50% of energy consumption in chemical plants. Therefore, intensified separation technologies and their control technologies have to complement higher selectivity of the reactions.
Advanced separations and further innovation in this area are required to significantly reduce energy consumption and costs. These technologies encompass, amongst others, integrated systems where tailormade membranes (e.g. for catalysis and separation) and membrane reactors can be coupled with continuous processes with high potential for in situ recovery and reuse of resources. Other advanced separation process technologies include reactive and/or enhanced distillation, adsorption technologies, advanced filtration systems, utilisation of alternative solvents or colloidal separation and concentration.

Various technology options can be considered, including:
- Flexible distillation columns designed for plants with load changes.
- New distillation concepts such as dividing wall columns, heat integrated distillation, cyclic distillation.
- Alternatives to distillation such as adsorption (chromatography), pervaporation and nanofiltration.
- Integrated reactive and hybrid separations technologies – as a specific process intensification approach - that can significantly reduce energy consumption by integration into one unit of (multi) reaction separation steps, or several separation processes.
- Development of more cost-competitive separation units for energy-efficient treatment of industrial gaseous effluents, including for further chemical valorisation of CO_2. (Activity 4.4).
- Improved technologies for pre-treatment of biomass (see Activity 4.5).
- Particular applications of alternative separation technologies include recovery of catalysts.

Optimisation of the design and engineering of separation operations would also include the development of specific materials, such as:

- Highly selective membranes: for hybrid separation systems, to make pervaporation economically viable for other industrial applications than current dehydration of alcohols.
- New organic solvent nanofiltration membranes.
- Zeolites, MOFs and hierarchical porous materials for advanced adsorption technologies at lower cost.

Tools supporting decision making from the early process/plant design phase of new processes to production management is essential, and the integration of digital technologies (see Systems Activity) will be critical for:

- Optimized (re-)design of chemical processes and plants including for structures, equipment, piping.
- Predictive assets management leading to maximum asset utilisation, less downtime and less energy consumption.
- Optimized production.
- Demand forecasting and supply chain optimisation.

Impact:

- Improved energy and resource efficiency.
- Improved robustness and flexibility.
- Reduction of energy required for advanced separation operations (upstream & downstream).
- Integration of more compact and robust systems (including antifouling and overall enhanced lifecycle), contributing to less capital-intensive system design.
- Performance improvements, beyond energy-efficiency: processing speed and improved process metrics (yield & selectivity).

Technical Readiness Level (TRL):

Developments are needed at all TRLs.

New distillation concepts already mature in some business cases but need to be applied in a broader scope. Alternatives have basically a lower TRL (especially membrane technologies like pervaporation or membrane distillation).

Gaps:

Non-technical gaps include:

- Cost of the new technologies developed (both capital expenditure and operational costs).
- Access to competitive renewable electricity for non-thermal separations.

9.5 Iron & Steel Activity Fiches

9.5.1 Activity 5.1 - CO_2 emissions avoidance through direct reduction of iron using hydrogen

Title: CO_2 emissions avoidance through direct reduction of iron using hydrogen		
TG: Steel sector	**Activity No: 5.1**	**Activity leader: Eurofer**
Targets[64]: Reduction degree of iron oxide: > 90 % (KPI2a) Replacement rate of fossil carbon by hydrogen injection: > 10 % (KPI2b) Replacement rate of natural gas by H2 in the feed of the direct reduction plant: > 50 volume-% (KPI2c)		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)** CO_2-Mitigation monitoring in ETS

Description:
The conventional way of iron ore reduction is based on carbon from the utilization of coke and coal. The new technology of iron ore reduction by the help of hydrogen can minimize the CO_2-Emissions significantly. At the moment, the technology of iron ore reduction by hydrogen is economically not feasible in Europe due to high OPEX. Against the background of the ambitious EU climate targets 2030 and in order to start the transition phase of integrated steel mills as soon as possible, significant investments (CAPEX) in this new plant technology (direct reduction plant (DRP), electric arc furnace (EAF) are required.

Further important aspects for the successful implementation of the hydrogen-based steel production is the availability of renewable energy at low cost for the production of green hydrogen and for the operation of electric arc furnaces. At the beginning of the transformation process, natural gas (NG) should be available at internationally competitive conditions to cover the volatile supply of green hydrogen, which will already reduce CO_2 emissions by two thirds compared to the coal-based blast furnace route.

Impact:
- Primary energy saving potential in percentage and in ktoe/a:
- GHG emission saving potential in percentage and in $ktCO_2eq/a$: ~180 Mio. t CO_2 / a (assuming full deployment in the EU)

Technology Readiness Level (TRL): Europe: 7-9 (9 for NG-based DRP)

Total budget required: N*ot supplied*

Expected deliverables	*Iron Ore Reduction based on Hydrogen without CO_2-emissions*	
Timeline	*Up to 2026*	
Parties / Partners	**Implementation financing / funding instruments**	**Indicative financing contribution**
Sweden	*National Funding*	*€8 m*
Germany	*European Funding and National Funding*	*€18 m*
Austria	*European Funding*	*€12 m*
Austria	*National Funding*	*€5.5 m*

Gaps:

At the moment, the technology of iron ore reduction by hydrogen is economically not feasible in Europe (mainly due to internationally uncompetitive OPEX). The main aspects for the successful transformation are the

[64] Target adapted from the Clean Steel Partnership's Objectives and KPIs. All targets from here correspond to 2030 objectives based on the KPIs. The corresponding KPIs are referenced in brackets next to each target e.g. (KPIx). Technologies considered in the targets are at TRL8 and above. *https://www.estep.eu/assets/Uploads/200715-CSP-Roadmap-version-public-consultation.pdf)*

availability of renewable energy and suitable input material at internationally competitive conditions for the production of green hydrogen and for the operation of electric arc furnaces. Additionally, a high amount of investment is required in the plant technology (direct reduction plant (DRP), electric arc furnace (EAF)) (CAPEX).

9.5.2 Activity 5.2 - CO_2 emissions avoidance through direct reduction of iron ore using electricity

Title: CO_2 emissions avoidance through direct reduction of iron ore using electricity		
TG: Steel sector	**Activity No: 5.2**	**Activity leader: Eurofer**
Targets[81]: Short term (2030): Electric efficiency of the electrolytic cell: > 85% (KPI3)		**Action 6 monitoring activities will draw on relevant industry publications.**

Description:
Electricity is an energy form that can be used to produce primary steel which is iron metal from mineral iron oxides. By the application of a voltage in an electrochemical cell, the flow of current decomposes metal oxide into metal at the cathode and oxygen gas at the anode. This technique, known as electrowinning, is widely applied to non-ferrous metals such as Ni, Cu and Zn in acid electrolytes. However, the multi valencies of iron ions was considered as an obstacle to the application of electrolysis to the iron metal.
This problem has been solved by the SIDERWIN process were electrolysis is carried out in alkaline solution where one of the two valencies, ferric iron, is insoluble and where iron oxide is reactive at solid state.
In the SIDERWIN processing route the mineral iron oxide is finely milled and then cleaned from gangue compounds before electrolysis. The electrolysis step is designed to address the magnitude of steel production with very large electrodes. Furthermore, the proximity of electrodes and the high reactivity of iron oxides are distinctive advantages to achieve high energy efficiency. Then, iron metal produced as metal plates is melted in induction furnaces and then follow the conventional processing route of steel. The confinement of the flows and the fine adjustment of different energy needs are contributing to reach high overall energy efficiency. The absence of lime plant, of carbon-based fuels and of carbon electrodes guarantee to reach carbon neutrality at the steel plant.
The carbon neutrality efficiency depends directly from the carbon content of the electrical energy input. To this regard, the process is designed to operate electrolysis at low temperature in order to be able to change quickly the electric energy consumption thus participating in the balance of the electrical grid. This flexibility of a large, controlled and monitored electrical energy consumer is a unique tool to help limiting emissions of CO_2 from peaking power plants and to integration more non-dispatchable renewable energy sources.
The project is led by ArcelorMittal. In the past 12 years the technology has been developed to TRL 4 through the manufacturing of 5 different pilots, proving the potential of the technology. With this solid background, ArcelorMittal surrounded by 11 European partners, aims at developing a 2.75-metre-long new experimental pilot to validate the technology at TRL 6.

TRL: 5-6

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
ArcelorMittal (Coordinator, France), JohnCockerill (Belgium), EDF (France), CFD-Numerics (France), QUANTIS (Switzerland), TECNALIA (Spain), UAVR (Portugal), Mytilineos (Greece), NTUA (Greece), N-Side (Belgium), Dynergie (France), NTNU (Norway)		

Gaps: None

9.5.3 Activity 5.3 - Process integration: HIsarna smelting reduction process for lowering energy consumption and CO_2 emissions of steel production

Title: Process integration: HIsarna smelting reduction process for lowering energy consumption and CO2 emissions of steel production		
TG: Steel sector	**Activity No: 5.3**	**Activity leader: Eurofer**
Targets[81]: Decrease the use of energy per tonne of steel for clean steel making: > 10 % specific energy consumption reduction for a dedicated process (KPI9)		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)** an explanation of how each target will be monitored and reported to SETIS. Monitoring of Activity progress will be done by regular progress meetings. Periodic reports to be provided to SETIS.

Description:

Achievement of the Target is directly related to a successful scale-up of the HIsarna technology. Up till now, five successful pilot plant campaigns between 2011 and 2019 in the pilot plant, at Tata Steel (NL) have brought the technology close to TRL 7. The pilot plant has a hot metal capacity of 8 t/h. In 2021, a sixth campaign will commence in which long-term operating stability as well as circular economy options will be tested. The pilot plant will be modified in preparation of an extension with an integrated CO2 capture facility.

The proposed R&I Activity will on the one hand further progress the pilot-plant research related to the sixth campaign and on the other hand focus on design, impact and financial aspects of a scaled-up demonstration plant. The Activity is an essential step in the development chain to bring the technology toward TRL≥8. In the R&I Activity, the following tasks are foreseen:

1. Circular economy: As part of the EIT Raw Materials ReclaMet project, tests will be carried out to enable recycling of plant residues (such as dust and sludges), with the aim to recover valuable elements, in particular Fe and Zn. In 2020 a preparation facility was installed at the HIsarna Pilot Plant to enable the co-injection of various reverts with the main ore injection. The goal of the ReclaMet project is to recover Zn in the HIsarna off-gas dust, at concentrated levels that will allow economic replacement of primary zinc ore in the zinc industry. This development will allow a high percentage of galvanised scrap to be recycled for strip steel products via the BOF steelmaking route.

2. CO_2 capture: HIsarna is an oxygen-based process and the top-gas is very rich in CO_2. Thus far, concentrations of 75% have been achieved on pilot-plant scale. From 2021 onwards, options will be tested at the pilot plant to replace air or nitrogen as pneumatic conveying gases, further increasing the CO_2 concentration in the off-gas. In 2019-2020 a pre-FEED study was performed to evaluate the most energy efficient CO_2 capture technology that utilises these high CO_2 concentrations. Based on this study, a pilot CO_2 capture facility will be designed, constructed and tested at the pilot plant. Integration of a continuous hot metal production with a continuous CO_2 capture unit would bring the project to TRL7.

3. Sustainable biomass: A project was started in 2020 to study the potential for treatment of large quantities of biomass to make it suitable for use/injection in HIsarna as a coal replacement, and the potential use of generated biogas (during biomass treatment step) for optimising a brown-field production site with respect to its gas and energy balance. This project contributes to a reduction of fossil raw materials and will enable net negative CO_2 emissions when combined with CO_2 capture and storage (CCS).

4. Preparations for a demonstration scale plant: In an earlier project, a conceptual design for a demonstration scale plant (~ 1 mton/a hot metal capacity) has been made. Several tasks need to be employed to prepare for an investment decision of such a plant.

a. Basic engineering study regarding the integration of HIsarna in a typical EU brown-field production site. Aspects that will be studied are amongst others: design of the core plant, its facilities and embedding of the plant in the existing site energy infrastructure (gas, electricity, etc).

b. Economic study, with specific attention for a brown-field site energy balance. Aspects that will be studied are amongst others: capital investment, operational costs, etc.

Impact:

- Primary energy saving potential in percentage and in ktoe/a (assuming full deployment in the EU27): HIsarna reduces energy consumption and specific CO_2 emissions based on choices for raw materials and CCS deployment.

a. HIsarna based on iron ore and coal, without CCS:
   20% energy saving, 20% CO_2 saving (compared to a reference integrated BF-BOF steelmaking site as defined in the ULCOS programme).
b. HIsarna based on addition of scrap (200 kg/t hot metal) and biomass (240 kg/thm), without CCS:
   35% energy saving, 55% CO_2 saving.
c. HIsarna based on iron ore and coal, with CCS:
   10% energy saving, 95% CO_2 saving.
d. HIsarna based on addition of scrap (200 kg/t hot metal) and biomass (240 kg/thm) with CCS:
   25% energy saving, 120% CO_2 saving (net negative emissions).

The energy saving potential for EU27 deployment, replacing all BF capacity in EU27 estimated at 100 Mt/annum, is estimated as follows (42 GJ = 1 toe):

a. 8,900 ktoe/annum
b. 15,600 ktoe/annum
c. 4,400 ktoe/annum
d. 11,200 ktoe/annum

- GHG emission saving potential in percentage and in ktCO₂eq/a (assuming full deployment in the EU27). If all EU27 blast furnace capacity (estimated at 100 Mton/annum) would be substituted with HIsarna, then emissions would be reduced, depending on the 4 options listed above, as follows:

a. 36 Mt CO_2/annum
b. 99 Mt CO_2/annum
c. 171 Mt CO_2/annum
d. 216 Mt CO_2/annum

Technology Readiness Level (TRL): Advanced research / Industrial research & demonstration / Innovation & market uptake. The TRL of this Activity would be “Industrial research & demonstration”. The current TRL is 6 (“technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)”). This Activity furthers several aspects that are needed in preparation for TRL7 (system prototype demonstration in operational environment) and beyond.

Total budget required: € 51 m for demonstration (~ €500 million for upscaling steps); financing: mix of private/public funding

Expected deliverables	**Timeline**	
1. Design and construction of CO_2 capture plant at pilot scale	*Month (1-36)*	
2. Basic engineering study for demonstration scale HIsarna plant	*Month (1-24)*	
3. Tests in pilot plant of zinc recycling, scrap usage, biomass and other coal replacements	*Month (1-36)*	
4. Tests in pilot plant with combined ironmaking production and CO_2 capture	*Month (37-48)*	
Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
1. Selection, design and construction of energy efficient CO_2 capture technology for HIsarna. (Tata Steel NL + suitable industrial partners + EU funding)	Foreseen is Private + Public funding	€ 25m (total cost)
2. Engineering for demonstration scale plant (Tata Steel NL + suitable industrial partners + EU)	Foreseen is Private + Public funding	€ 8m

3. Long-duration tests at Pilot Plant scale including zinc recycling, scrap usage, biomass and other coal replacements (Tata Steel NL + suitable industrial partners + EU)	Foreseen is Private + Public funding	€ 12m
4. Long-duration of combined ironmaking and CO_2 capture (Tata Steel NL + suitable industrial partners + EU)	Foreseen is Private + Public funding	€ 6m

Gaps: None

9.5.4 Activity 5.4 - Process integration: Top Gas Recycling – Blast Furnace (TGR-BF) using plasma torch

<table>
<tr><th colspan="3">Title: Top Gas Recycling – Blast Furnace (TGR-BF) using plasma torch

The steel industry can lower its carbon consumption (and thus GHG emissions) by the dry reforming of steel mill CO_2 in a plasma torch with renewable electricity. For this reaction, methane from coke oven gas or natural gas can be used. The CO_2 is in the BF or BOF gas that will be recycled and heated for injection into the blast furnace.</th></tr>
<tr><td>TG: Steel sector</td><td>Activity No: 5.4</td><td>Activity leader: Eurofer</td></tr>
<tr><td colspan="2">Targets:

This project is a first step on the way to develop a new generation of Top Gas Recycling Blast Furnace. This TGR-BF project will recover all CO + H_2 in the top gas of the blast furnace, for re-injection in the furnace. This will increase the C-efficiency in the furnace by 80%.

The dry reforming of steel mill CO_2 with CH_4 will help to develop all necessary technologies for the design of a new generation TGR-BF i.e. the refractory for heating gases, the design of the furnace, the tuyere for top gas injection, the operation practices. The goal is to have the industrial furnace ready for operation before 2030.</td><td>Action 6 monitoring activities will draw on relevant industry publications.

Possible primary data collection to monitor progress (not monitored under SET Plan) one (or more) plasma torches will be installed on the tuyeres of a blast furnace the gas flows, analysis and energy consumptions (coke, oxygen, electricity) will be measured
the CO_2 emission will be calculated through Life cycle Assessment calculations.</td></tr>
</table>

Description:
The steel industry can lower its carbon consumption (and thus GHG emissions) by the dry reforming of steel mill CO_2 in a plasma torch with renewable electricity. For this reaction, methane from coke oven gas or natural gas can be used. The CO_2 is in the BF or BOF gas that will be recycled and heated for injection into the blast furnace.
The TGR-BF project consists of several phases including the design of a plasma torch for steel mill gas conversion , the design of a novel tuyere allowing to inject coal, oxygen and hot reformed steel mill gas into the blast furnace, the engineering and construction of all this equipment on one European blast furnace (BF 2 in Dunkirk), the testing of this equipment and once these parameters are determined, these values and designs can be used to start the study of a full Top Gas Recycling Blast Furnace. This study may well take another 4 years. Construction may take another 2 to 3 years. The goal is to have the industrial furnace ready for operation before 2030.

Impact:
Primary energy saving potential in percentage and in ktoe/a (assuming full deployment in the EU27 + UK)

- The impact of the plasma torch project is estimated at 325 MJ per ton of crude steel. Assuming a yearly EU conventional steelmaking capacity of 116 Mt, this amounts to 37.7 million GJ/y or 900 ktoe/a.
- The impact of the TRG-BF without CCS is estimated at 1.993 MJ per ton of crude steel. Assuming a yearly EU conventional steelmaking capacity of 116 Mt, this amounts to 231 million GJ/y or 5.500 ktoe/a.
- Important remark: the energy savings of the two stages of the project are not cumulative.

GHG emission saving potential in percentage and in ktCO_2eq/a (assuming full deployment in the EU27 + UK)

- The impact of the plasma torch project is estimated at 89 kg of CO_2 per ton of crude steel. Assuming a yearly EU conventional steelmaking capacity of 116 Mt, this amounts to 10.3 Mt/a of CO_2.
- The impact of the TRG-BF without CCS is estimated at 306 kg of CO_2 per ton of crude steel. Assuming a yearly EU conventional steelmaking capacity of 116 Mt, this amounts to 35.5 Mt/a of CO_2.
- If the TGR-BF is combined with a storage project of the CO_2 then the potential raises to 1.052 kg of CO_2 per ton of crude steel. Assuming a yearly EU conventional steelmaking capacity of 116 Mt, this amounts to 122 Mt/a of CO_2.
- Important remark: the CO_2 savings of the two stages of the project are not cumulative.

Technology Readiness Level (TRL): Industrial research & demonstration
TRL at start: 6 for Plasma torch, 7 for conventional TGR-BF; at end: 8.

Total budget required:

- €16m for testing of 1 tuyere on a blast furnace.
- €79m for the plasma torch dry reforming project.
- Over €400m to construct the Top Gas Recycling Blast Furnace (this is a rough estimate based on the former ULCOS project that applied for NER 300 funding).

Expected deliverables	**Timeline**
• Development of adequate refractory materials, metals and coating. Mastering of the metal dusting and carbon deposit problem. • Development of a novel tuyere (combination of O_2, pulverised coal and hot syn gas). • Development of a plasma torch, easily switchable, to add the electrical energy to the gas. • Design of a gas mixing chamber to quench the hot syn gas from the plasma torch.	• Tuyere design, test and trial program = years 2017 – 2023). Roll out of the plasma technology on blast furnaces after 2025. • Design of the Top Gas Recycling Blast Furnace using the elements of the plasma trials years 2023 – 2025. • Engineering, design of the TGR-BF = years 2023 – 2025. Construction of the TGR-BF, commissioning and trial programs = years 2026 – 2030. Full production after 2030.

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
• Plasma torch suppliers. • Electrical control equipment. • Development of heat resistant. • Development of heat resistant refractory. • Design and casting of tuyeres. • Integration engineering. • Industrial gas suppliers for gas separation and treatment Steel companies from EU27 + UK and all over the world.	*Private equity and debt* *National funding organisations (ADEME (Fr), BMBF (Ger), ISPT+ RVO (Neth., Agentschap ondernemen (Bel))* *European funding: Horizon Europe, notably Processes4Planet and Clean Steel partnerships, Circular Economy; the Innovation Fund...* *European financing instruments (EIB-EFSI, notably the InnovFin Energy Demonstration Projects …)*	…

Gaps: None

9.5.5 Activity 5.5 - Carbon Capture and Usage

Title: Re-use of carbon of steelmaking by usage of the steel mill gases as syngas for fuels or chemical products. The usage of CO and CO_2 (without or in combination with H_2) as a resource allows us to reduce the total carbon footprint		
TG: Steel sector	**Activity No: 5.5**	**Activity leader: Eurofer**
Targets: In the existing conventional steel and chemical plants, industrial by-product gases are used for electricity production. This power production is preventing the instalment of additional renewable capacity. The target is to store, as much as possible, carbon emissions from industrial processes into fuels and chemicals, instead of the use of the calorimetric content and emitting the exhausting products. **Short term (2031)**[81]: CO2 capture rate from process/off-gases: > 95 % from dedicated gas streams (KPI6)		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)** The production of fuels and chemicals is determining the CO_2 reduction potential. A large measurement program will be set up which allows the monitoring of results and doing an accurate LCA of the technology.

Description:
The conversion of CO and CO_2 (without or in combination with H_2) may allow using carbon from steel mill exhaust gases as feedstock (carbon source) for new products (fuels and chemicals). Hence the carbon is used a second time as resource rather than being emitted. The conversion can be biological transformation by algae into new organic compounds or chemical transformation into chemical building blocks for the chemical industry or synthetic fuels for the transport sector. It can also be mineralisation, e.g. for making building materials. Notably two processes based on chemical transformation are of particular interest in the steel sector: the ethanol fermentation project STEELANOL that is being developed in Belgium Flanders and the cross industrial project Carbon2Chem located in Germany, Duisburg.
The proposed STEELANOL project is based on producing bioethanol via an innovative gas fermentation process using exhaust gases emitted by the steel industry – instead of using them for electricity production. Hence, this will reduce the usage of fossil fuel molecules and thus significantly reducing GHG emissions. The bio-ethanol production would have a GHG impact that is over 65% lower compared to oil derived fuels. STEELANOL’s main objective is to demonstrate the cost-effective production of sustainable bioethanol, with the purpose of assessing the valorisation of this ethanol biofuel as a fuel derivative for the transport sector. The construction of a demonstration plant of approximately 25,000 tons/ethanol per year started in 2019; the first of its kind in Europe, and the largest facility built to date utilizing this technology globally. ArcelorMittal is the lead partner of this project and proposal. The gas fermentation technology is supplied by LanzaTech, the engineering work is performed by Primetals, and E4Tech has been in charge of developing the Life Cycle Assessment of the produced fuels. Several key players in the transport sector, Boeing, Virgin Atlantic, Mitsui, have expressed their strong interest and support for the project.
On May 18th 2020, the European Investment Bank, with the support of the European Commission, has granted a € 75 million loan to ArcelorMittal for the construction of two ground-breaking projects at ArcelorMittal Ghent: Steelanol and Torero (a large-scale demonstration plant to convert waste wood into bio-coal).
ArcelorMittal is also planning to expand its use of this technology. At ArcelorMittal Fos-sur-Mer, France, a study is underway in collaboration with partner Lanzatech, to build a second plant in addition to the one under construction at ArcelorMittal Ghent in Belgium. This involves carbon capture from the blast furnace waste gas, and biologically converting it into ethanol for use as a biofuel or recycled carbon feedstock for the chemical industry.
The approach of the Carbon2Chem project is to convert process gases from the steel production – including the CO and CO_2 they contain – into base chemicals on an industrial scale level. The CO_2 of one industry becomes the raw material of the next industry. This is a first step to a new level of circular economy. With this strategy greenhouse gases would then no longer be discharged into the atmosphere. This carbon usage across industries is a concrete step in a low carbon industrial process but requires an optimization across the individual industrial subsystems. An optimisation of the total system could result in higher CO_2 reduction potential than the sum of single individual optimisation efforts. Beside the CO_2 reduction, Carbon2Chem also supports the stability of the electrical grid (grid support) by the usage of volatile renewable energy for the hydrogen production and thus have a positive contribution to the “energy transition” in Germany.

Carbon2Chem is characterised by broad-based, cross-industrial cooperation. It helps to create a new network of steel production, electricity generation and chemical production. Partners from the areas of basic and applied research and various sectors of industry are involved in the project. Thyssenkrupp and the Max Planck Institute for Chemical Energy Conversion have carried out preparatory planning and scientific work.
At least ten years of development work will be needed before the process is ready for industrial-scale use.
Carbon2Chem's prospects of success are good because the basic chemical processes and required technologies are largely known. It is already technically possible to convert process gases from steel production into ammonia as a starting product for fertilizers, though not yet cost-efficiently. Another possibility would be to produce higher alcohols from mill gases. Production of methanol and ammonia from cleaned steel-mill gases has been already successfully proved at laboratory scale.
In order to use renewable energies for chemical conversion, catalysts would be required that can cope with sharp fluctuations in the process. Currently, long-term campaigns for the synthesis of methanol are being done in order to prove the stability of the catalyst and the technology in general. Cost-efficient methods of producing hydrogen – even with sharp fluctuations in the energy supply – will also have to be developed. Cleaning and processing the steel mill gases is another area of current research.
Since it was launched in March 2016, "Carbon2Chem" has already made great progress in its first phase (2016 - 2020). The joint technical centre at the Thyssenkrupp site in Duisburg was inaugurated in September 2018. This is where the individual processes are practically combined and tested under industrial conditions in practical operation with real steel mill gases. The inauguration of the project's own laboratory at Fraunhofer UMSICHT in Oberhausen followed in March 2019. The partner consortium is working together on processes for gas cleaning and for the production of methanol and higher alcohols and scaled up for industrialisation from 2025.
The second phase (2020 -2024) is dedicated to (1) the demonstration of long-term stability, (2) the application of Carbon2Chem technology in other industries and (3) the development of business cases. In this second phase, the lead project will deal intensively with the composition, cleaning and treatment of the steel mill gases at the Thyssenkrupp site in Duisburg. This is the starting point for the three sub-groups that deal with the different product pathways, methanol, higher alcohols and polymers. A separate project deals with the transfer of Carbon2Chem technology to various CO_2 point sources such as waste incineration, lime and cement plants. Finally, the individual modules are brought together in an optimized, coherent system network through an overarching lead project. For this system integration, simulation calculations and models are created, and studies of economic efficiency and ecological effects are carried out. In order to test the future supply of the steelworks with hydrogen, different ways for the supply of renewable energies are being investigated. For this purpose, import chains are being modelled and the possibility of using ammonia as a hydrogen carrier is investigated experimentally.
With "Carbon2Chem", partners from science and industry are building a bridge from basic research to the market.
The Federal Ministry of Education and Research funded the project with more than 60 million euros in the first phase. The BMBF provided further €75 million for the second phase. The partners involved are planning investments of more than €100 million by 2025. They have earmarked more than €1 billion for commercial implementation.

Impact:

Impact of STEELANOL

-Primary energy saving potential in percentage and in ktoe/a

If all steel mill gases of the EU-27+UKconventional steel plants (BF-BOF route) are converted into ethanol the yearly production potential is approximately 14.5 million t/y of EtOH. This is the storage of 350 million GJ/y. The fermentation takes 116 GWh of electricity production away from the European continent. This capacity can be replaced by renewable production capacity (geo-thermal, wind, photovoltaic).

-GHG emission saving potential in percentage and in ktCO_2eq/a

If all steel mill gases of the EU-27+UKconventional steel plants (BF-BOF route) are converted into ethanol the yearly production potential of approximately 14.5 million t/y of EtOH will reduce CO_2 emissions from industry by 33.3 million tons/y.

Impact of Carbon2Chem

If all steel mill gases of German conventional steel plants (BF-BOF route) are used by Carbon2Chem for chemical bulk products, it will reduce CO_2 emissions from industry by 20 million tons/y in Germany.

Technology Readiness Level (TRL):
STEELANOL: The current TRL is between 8 and 9. Construction of a demonstration plant is ongoing, the ethanol fermentation project STEELANOL is being developed in Belgium Flanders. A legal framework needs to be defined within the EU, in order to create a market of such CCU-technologies and –products.
Carbon2Chem: Current TRL of Carbon2Chem lies between 8 and 9. Existing Steel and Chemical processes, which are intended to be used in Carbon2Chem, are already reliable running technologies on an industrial scale. The challenge of Carbon2Chem is to combine their large-scale industrial processes (cross-industrial network).

Total budget required:

Total budget required (based on the STEELANOL project in Gent – Belgium) For the engineering, design, construction, commissioning of the fermentation plant, trial and operational testing: €164 m.

Total budget required (based on the Carbon2Chem project – Germany) The first phase is already funded with €60 m by the German authorities. For the second phase, the upscaling and operating to a small to medium industrial plant would require approximately €500 m.

Expected deliverables	Timeline
STEELANOL Development of the gas treatment technologies, and novel separation technologies. **Carbon2Chem** A cross industrial solution for steel mills exhaust gases as feedstock for chemical bulk materials General proof of rollout potential on other GHG intensive industries (e.g. cement, lime, waste incineration). Strategies to handle high volatility in large scale industrial production processes.	Construction of a demonstration plant, commissioning and trial operation = 4 years (2017-2021) Further development and rolling out the technology: after 2022. Four years for the first demonstration plant. Additional two to four years to demonstrate the process reliability with gases from a steel mill. A first large-scale plant will not be available before 2030.

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**

Partners of STEELANOL project: Distillation and condensation technology providers (GEA (Ger), Vogelbush (Aus), Sulzer (Switz), Katzen (USA)). Compression equipment (Siemens, Borsig, Ingersoll, (Germ/It)). Other gas treatment technology providers: (Ger, Fra, It, Spain). Design and construction of reactors (Pol, Czech, Ger) Integration engineering (Jacobs, Arcadis, Foster Wheeler, Technip, (It, Fra, Germ)). Industrial gas suppliers for gas separation and treatment (Dow (Neth), MHPSE, Linde (Ger), Air Liquide (Fra)). Steel companies from EU27 + UK and all over the world. Bio chemical technology developers and providers (Lanza Tech (UK)). Universities/institutions for the research of the technologies (BBEU, Nova, Fraunhofer (Fra, UK? Germ, Spain)). **Partners of Carbon2Chem project** <u>L-0: System Integration</u> Partner: thyssenkrupp AG, Max-Planck-Institut-CEC, Fraunhofer UMSICHT, Siemens. <u>L-1: CO_2 Sources and Infrastructure</u> Partner: thyssenkrupp AG, Fraunhofer UMSICHT, Lhoist Germany Rheinkalk GmbH, Remondis SE & Ko. KG. <u>L-2: Sustainable methanol production</u> Partner: thyssenkrupp AG, Nouryon Industrial Chemicals GmbH, Clariant Produkte GmbH, Fraunhofer UMSICHT, Fraunhofer-ISE. <u>L-3: Gas cleaning</u> Partner: thyssenkrupp AG, Linde AG, Clariant Produkte GmbH, Fraunhofer UMSICHT, Ruhr Universität Bochum. <u>L-4: Higher alcohols / polyalcohols</u> Partner: thyssenkrupp AG, Evonik Industries AG, Ruhr Universität Bochum, RWTH-ITMC, Fraunhofer UMSICHT. <u>L-5: Polymers</u> Partner: thyssenkrupp AG, Covestro produkte GmbH, Max-Planck-Gesellschaft, RWTH.	*National funding organisations (ADEME (Fr), BMBF (Ger), ISPT+ RVO (Neth).., Agentschap ondernemen (Bel))* *European funding: Horizon Europe, notably Processes4Planet and Clean Steel partnerships, Circular Economy; the Innovation Fund; the European Investment Bank, notably the InnovFin Energy Demonstration Projects ...* *National funding by the German federal ministry of education and research (BMBF)*	…

Gaps: None

9.5.6 Activity 5.6 - Circular economy

Title: Circular economy		
TG: Steel sector	**Activity No: 5.6**	**Activity leader: Eurofer**
Targets: Enhanced recycling of steel (such as ferrous scrap) and enhanced utilisation of steel by-products (such as slag) as well as increased recovery waste heat to increase resource and increased energy efficiencies in both primary and secondary steel production routes. **Short term (2030)**[81]**:** Re-use and recycling of solid residues co-generated during the steel production process and reduction of their landfilling rate: internal and external recycling and re-use rate > 85 % (in total) (KPI10) Low-quality scrap input share over the total scrap input increased by at least 50% or more compared to the usual practice for a specific steel quality (KPI11)		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)** CO_2-Mitigation monitoring in ETS, efficiency improvements

Description:
Circular economy (CE) approaches enhance the recycling of steel (e.g. ferrous scrap in BOF/EAF and residues) and resource efficiency. CE promotes the scrap utilisation through scrap sorting and improved removal of scrap pollution with new detecting technologies. It also includes processes related to the enhanced utilisation of all residues from steel production internally or in other sectors like dust in the non-ferrous sector or slags in the cement sector. Besides, CE supports the substitution of fossil materials with alternative carbon-bearing materials and alternative reductants (e.g. biomass, plastic, rubber, syngas from wastes). Finally, CE approaches encompass technologies that identify and make use of waste heat sources.

Impact:
- Primary energy saving potential in percentage and in ktoe/a (assuming full deployment in the EU27 + UK)
- GHG emission saving potential in percentage and in ktCO2eq/a (assuming full deployment in the EU27 + UK)

Technology Readiness Level (TRL): Advanced research /Industrial research & demonstration / Innovation & market uptake. Also mention TRL at start and envisaged at the end

Total budget required: TBC

9.6 Pulp & paper Activity Fiches

TO NOTE: Due to competition laws, project-specific and some general information cannot be provided.

9.6.1 Activity 6.1 – Integral drying and heat recovery processes

Title: Integral drying and heat recovery processes		
TG: Pulp & Paper	**Activity No: 6.1**	**Activity leader: Cepi**
Targets: Short-term: Demonstration of Integral drying and heat recovery innovations in operational industrial environment by 2030. Long term: Further market penetration of 40% by 2050, subject to the success of the 'competing technologies' being developed simultaneously (see the other Activity fiches).		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)** R&D results moving towards higher TRL levels, industry and supplier involvement in the initiatives.

Description:
Innovative heat recovery processes, like mechanical vapour recompression and other kind of heat pumps may realize a significant reduction of energy required for steam production. However, effective use of these techniques inherently requires a starting vapour at a high temperature and low air content. Though drying technologies in paper making processes are highly efficient in achieving almost 100% energy transfer for water evaporation, the processes are not designed to result in a vapour of which heat can efficiently be recovered. The challenge is to develop new drying processes that result in clean airless vapour. These innovations will thus be focused drying technologies that allow efficient heat recovery from the vapour (e.g. superheated steam drying, air/vapour separation). These innovations may use more electricity than heat as energy source.

Impact:
When sufficient, competitively priced renewable electricity is available the replacement/adjustment of the traditional drying equipment with a combined drying/heat integration innovation may on mill level result in up to 40% energy savings of total paper process energy consumption[65]. Actual CO_2 savings will depend on the local energy mix.

Technology Readiness Level (TRL): TRL: 3, TRL target: 9

Total budget required:
R&D: €50 million (in case of one large joint development program – fragmentation will lead to higher costs).
Demo : €100 million.
First flagship: €400 million.

Expected deliverables	Heat integration process designs (potential for heat pump technologies assuming optimal vapour quality) Dry solids separation from drying exhaust Direct/Indirect condensation and heat pumping Air-vapor separation (by sorption or membranes) and vapor compression Addition of super-heated steam and / or electromagnetic heating Airless drying technologies
Timeline	First integration up to 2030.

[65] Total Energy consumption (incl. Net Bought electricity) in the pulp and paper industry is: 1 312 508 TJ. Total CO_2 emissions in the pulp and paper industry (2019): 31.1 Mton. Savings obtained with the activities in this fiche only hold for the paper production part. – Cepi Key Statistics 2019.

	Further market penetration will continue after 2030. The percentage of market penetration will depend on the success of the 'competing technologies' being developed simultaneously (see the other Activity fiches) implementation of which may result in a 'lock-in' for the other innovations

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
European pulp and paper companies Developers and suppliers of heat pump technologies (industrial partners), Developers and suppliers of drying and gas treatment technologies (industrial partners + research institutes), Integration engineering experts	R&D funding (national, Horizon Europe), Funding for pilots and demo's and first implementation (e.g. Innovation Fund), European financing instruments (EIB etc.), Private equity and debt	R&D: 50 € million Demo: 80 € million First flagship: 200 € million

Gaps:
Development and implementation of electricity-driven technologies to improve energy efficiency of heat-driven processes requires access to sufficient competitively priced electricity. This requires both developments in electricity infrastructure and financial mechanisms to either reduce the electricity price or compensate for the higher prices compared to natural gas. Other aspect to deal with is the loss of efficiency in Combined Heat and Power plants (CHPs). Most paper mills obtain their heat from their own CHP's. These CHP's are highly efficient in converting energy into both heat and electricity. The deliverables in this activity fiche most probably lead to a lower need for steam, and thus also the electricity production in the CHP will decrease. To prevent that the CHP capacity is not optimally used resulting in higher costs per MW, adjustments are required. E.g. running at full capacity, while supplying heat to somebody else or converting the excess heat into electricity with for example an Organic Rankine Cycle or a Steam Turbine, and use the electricity for its own processes or for selling to the grid, storage in batteries or conversion to H_2. Other options are upgrading or retrofitting the CHP to a more flexible system matching potential lower energy needs or changed balance in heat/electricity in the future. Each of these options mean crucial investments to ensure process efficiency indeed leads to overall savings in CO_2 emission and operational costs. This is to be included in investment decisions as well as supporting financial instruments.
Additionally, in order to stimulate industries to invest in innovative technologies additional guarantee funds are needed to compensate for the (risk of) loss of production and product quality, as to stimulate overcoming teething problems.

9.6.2 Activity 6.2 – Paper making without water evaporation

Title: 4.3 Paper making without water evaporation		
TG: Pulp & Paper	**Activity No: 6.2**	**Activity leader: Cepi**
Targets: **Short term:** Demonstration of Paper making without water evaporation technology in in operational industrial setting by 2040. **Long-term:** Successful demonstration will lead to commercial application, leading to >10 commercial scale plants in 2050. Further market penetration is subject to the success of the 'competing technologies' being developed simultaneously (see the other Activity fiches).		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)** R&D results moving towards higher TRL levels, industry and supplier involvement in the initiatives.

Description:
Paper owes its strength and stiffness to the presence of hydrogen bonds between the cellulose fibres. Therefore, effectively breaking and forming these bonds by addition and removal of water has been the core of paper making processes since its invention more than two millennia ago. However, the presence (and especially the removal) of water is the main cause behind the high energy consumption in current paper making processes. This could either be solved by technologies that can isolate water from a wet paper web without evaporation or by totally eliminating water from the papermaking process. In both cases the challenge is how to induce hydrogen bonded paper without the presence and evaporation of large amounts of water. This would mean a complete plant redesign.

Impact:
On average 70% of the energy required for paper making is thermal heat used for thermal drying. The energy savings due to innovative 'water removal technologies' will depend on the efficiency of the (probably electrically driven) new technologies. When paper could be produced without water, the energy consumption total drying process will be eliminated, but will be replaced with another (probably electrical) energy consuming process. When sufficient competitively priced renewable electricity is available alternative water removal may on paper mill level result in up to 20% saving of the drying energy so up 14% ion total energy consumption, production without water may on mill level result in up to 50% saving of the drying energy so up 35% on total energy consumption. Actual CO_2 savings will depend on the local energy mix[66].

Technology Readiness Level (TRL): TRL: 2, TRL target: 9

Total budget required:
R&D: 100 € million; Demo : 300 € million ; First flagship: 800 € million

Expected deliverables	Alternative water removal technologies (e.g. sorption, $scCO_2$, extraction, etc). Alternative hydrogen bonding inducing technologies.
Timeline	First flagship in 2040.

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
European pulp and paper companies, Equipment suppliers, Research institutes and universities.	R&D funding (national, Horizon Europe). Funding for pilots and demo's and first implementation (e.g. Innovation Fund). European financing instruments (EIB, etc. Private equity and debt.	R&D: 50 € million Demo: 240 € million First flagship: 400 € million

Gaps:

[66] Total Energy consumption (incl. Net Bought electricity) in the pulp and paper industry is: 1 312 508 TJ. Total CO_2 emissions in the pulp and paper industry (2019): 31.1 Mton. Savings obtained with the activities in this fiche only hold for the paper production part. Cepi Key Statistics 2019.

Real breakthrough technologies would require complete rebuild of current plants. Just like a person would not buy a new house, when they could not sell their old house, the paper industry will not just disinvest in their still well working plants to replace it by something completely new. This is not typical for the paper industry, but also holds for the other energy and capital-intensive industries. It is crucial to develop financial solutions to solve this 'stranded asset' problem and stimulate complete rebuilds.

Development and implementation of electricity-driven technologies to improve energy efficiency of heat-driven processes requires access to sufficient competitively priced electricity. This requires both developments in electricity infrastructure and financial mechanisms to either reduce the electricity price or compensate for the higher prices compared to natural gas.

9.6.3 Activity 6.3 – Process optimisation and electrification (modular approach)

Title: Process optimisation and electrification (modular approach)		
TG: Pulp & Paper	**Activity No: 6.3**	**Activity leader: Cepi**
Targets: **Short-term (2030):** Demonstration of Process optimisation and electrification in operational industrial setting **Long-term (2050):** Successful demonstration of modular technologies will lead to a fast further market penetration reaching between 10 and 70%, depending on the specific modular technology and subject to the success of the 'competing technologies' being developed simultaneously (see the other Activity fiches).		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)** R&D results moving towards higher TRL levels, industry and supplier involvement in the initiatives

Description:
Unit process optimisation and intensification can lead to energy savings in several parts of the process. This includes mild repulping technologies, more effective fibre refining technologies and innovative mechanical dewatering technologies so that less thermal drying is needed. Electricity-based technologies in dewatering and drying (e.g. microwave and ultrasound) may also lead to increased energy efficiency.

Impact:
This modular approach may lead to 2-5% savings on the level of a process unit (one modular innovation) in an individual pulp or paper mill. Some modular innovations may be combined, adding up to reach a maximum potential of up to 25% energy savings on mill level.[67] Actual CO_2 savings will depend on the local energy mix.

Technology Readiness Level (TRL): TRL: 2-6 (depending on the technology), TRL target: 9

Total budget required: R&D: €100 million; Demo: €200 million; First flagship: €200 million[68]

Expected deliverables	Mild repulping technologies More effective fibre refining technologies, Innovative mechanical dewatering technologies Advanced process control e.g. by machine learning and digital twins Heat storage during breaks Electric drying assisting technologies Demand side flexibility Hydrogen to increase pulp mills product portfolio New systems eliminating or minimizing the use of vacuum
Timeline	Integration of these modular technologies will take place gradually over time. First industrial implementation of all of these technologies will take place before 2030.

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
European pulp and paper companies, Equipment suppliers, Research institutes and universities	R&D funding (national, Horizon Europe), Funding for pilots, demo, first implementation (e.g. Innovation Fund), European financing instruments (EIB etc.), Private equity and debt.	R&D: €50 million Demo: €160 million First flagship: €100 million

Gaps:
Development and implementation of electricity-driven technologies to improve energy efficiency of heat-driven processes requires access to sufficient competitively priced electricity. This requires both developments in electricity infrastructure and financial mechanisms to either reduce the electricity price or compensate for the higher prices compared to natural gas. Additionally, in order to stimulate industries to invest in innovative technologies additional guarantee funds are needed to compensate for the (risk of) loss of production and product quality, as to stimulate overcoming teething problems.

[67] Total Energy consumption (incl. Net Bought electricity) in the pulp and paper industry is: 1 312 508 TJ. Total CO2 emissions in the pulp and paper industry (2019): 31.1 Mton – Cepi Key Statistics 2019.
[68] Total for several projects on modular technologies

9.6.4 Activity 6.4 – Mild pulping technologies

Title: Mild pulping technologies		
TG: Pulp & Paper	**Activity No: 6.4**	**Activity leader: Cepi**
Targets: **Short-term**: First commercial implementation by 2030 **Long-term:** Further market penetration will continue after 2030, up to 50% in 2050.		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)** R&D results moving towards higher TRL levels, industry and supplier involvement in the initiatives

Description:
The pulping processes currently applied are very effective and CO_2 neutral. They isolate high quality cellulose fibres, while the remaining lignin serves as a sustainable energy source feeding the process and pulping chemicals are being recovered. However, the increasing demand for biobased feedstock to replace fossil feedstock in chemicals and materials, calls for a pulping process with a lower energy demand allowing the lignin side stream to be used as feedstock for new materials while keeping a CO_2 neutral process. The challenge is to realize energy-efficient integral fractionation processes that isolate and convert all wood components into high-value applications: high quality cellulose for papermaking and lignin and hemicellulose-based components to replace fossil-based chemicals. As a continuation of ongoing EU and national projects, the activities will be on the one hand further progressing the research on pilot and demo scale and, on the other hand fundamental research to tailor the natural cooking liquids an recovery processes to achieve higher quality products at higher efficiency.

Impact:
Milder pulping technologies will not have an impact on the CO_2 emission of the pulp mills, as due to the utilisation of part of their biobased feedstock as energy source these mills are already CO_2-neutral. The impact will lay in the fact that at lower energy needs for pulping, these wood-based side streams will become available as valuable raw material source replacing fossil oil. Towards 2050 this may lead to up to 5 million tons of lignin becoming available as feedstock for biobased chemicals and materials. Roughly estimated, this would mean an energy saving of 200 PJ in the chemical industry (energy consumption of fossil feedstock for aromatic hydrocarbon chemicals, i.e. about 43 GJ/t with reference to benzene, toluene and xylene[69])

Technology Readiness Level (TRL): Technical Readiness Level: 4, Technical Readiness Level target: 9

Total budget required: R&D: €15 million; Demo: €50 million; First flagship: €400 million

Expected deliverables	Full valorisation of lignocellulose: high quality cellulose fibres for papermaking; Isolating lignin and hemicellulose-based compounds with a high application potential in the chemical industry; Applications for the residual fraction of extractives and minerals from the wood Recovery processes for the new pulping liquid (to be recycled internally) and for the dissolved components; Validation of the total concept (delignification + regeneration cycles) Total process concept that has a lower energy intensity compared to the conventional pulping process and resulting in a lower CO_2 footprint of the chemical sector utilizing the side products.
Timeline	First flagship in 2030. Further market penetration will continue after 2030, up to 50% in 2050.

Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
European pulp and paper companies, Equipment suppliers, Research institutes and universities	R&D funding (national, Horizon Europe) Funding for pilots and demo's and first implementation (e.g. Innovation Fund), European financing instruments (EIB,), Private equity and debt	R&D: €15 million Demo: €40 million First flagship: €200 million

[69] Tracking industrial energy efficiency and CO_2 emissions, IEA, in support of the G8 Action plan, 2007.

Gaps:
Real breakthrough technologies would require complete rebuild of current plants. Just as people do not buy a new house when they cannot sell their old house, the paper industry will not just disinvest in their still well working plants to replace it with something completely new. This is not just true for the paper industry, but also holds for the other energy and capital-intensive industries. It is crucial to develop financial solutions to solve this ‘stranded asset’ problem and stimulate complete rebuilds.
The large CO_2 savings from this concept will evolve in another sector than the investing sector. The current Climate policy does not stimulate to innovate to decrease the CO_2 emissions in other value chains. At the same time, customers are not stimulated to ask for products with lower CO_2-footprint.
It is crucial to get a CO_2 calculation methodology that stimulates total system / chain efficiency so that savings in one part of the system do not lead to increased emissions elsewhere.

9.6.5 Activity 6.5 – Onsite renewable energy conversion

Title: Onsite renewable energy conversion		
TG: Pulp & Paper	**Activity No: 6.5**	**Activity leader: Cepi**
Targets: **Short-term** (2030): Demonstration and implementation of innovative technologies up to 2030.		**Action 6 monitoring activities will draw on relevant industry publications.** **Possible primary data collection to monitor progress (not monitored under SET Plan)** *Growing number of implemented installations*

Description:
The bio-based character of the pulp and paper sector inherently provides the opportunity to utilise side streams as a renewable energy source. Although this has been used for decades, innovative technologies offer opportunities to significantly increase resource, cost and energy efficiency. Moreover, thanks to biomass incinerated on-site with carbon capture and storage (BECCS), the sector can achieve negative emissions.
The processes currently applied by pulp mills are very effective and CO_2-neutral. They isolate high-quality cellulose fibres, while the remaining lignin in the so-called 'black liquor' serves as a sustainable energy source feeding the process. Pulping chemicals are simultaneously recovered as a main product. Emerging technologies like gasification, torrefaction, carbonisation and pyrolysis offer wider opportunities for the valorisation of the side streams and thus increased resource efficiency. These technologies also provide opportunities for conversion to other products. The challenge is to simultaneously recover the pulping chemicals to be re-used in the pulping process and to produce new fuels or chemicals.
Other by-products from forest-based industries, such as sawdust, bark and tall oil, can also be used efficiently towards new products. By far, the largest market opportunities exist for fuel and energy products. Commercial-scale bio-based facilities already operate, among others, for the extraction of biodiesel from tall oil or the production of biomethanol from pulp mill side streams.
Onsite biogas production through anaerobic wastewater treatment is commonly applied at recycled paper mills. Innovations may further increase this renewable energy potential by digestion of sludges and regional cooperation in (co-)digestion of other organic waste streams such as manure or garden waste. Research also progresses on the valorisation of wastewater towards higher added value components. Biogas strengthens the business case for high-efficient CHP, thus delivering energy savings for the total energy system.
Other biomass-containing side streams from recycled paper mills, like rejects, are also valuable energy sources that can be incinerated. For more efficient energy use these rejects can be gasified or liquified. The challenge in the development and commissioning of these processes is the heterogeneous character of the rejects.
Another relevant emerging technology is solar heat. Concentrated solar thermal systems can generate steam at the temperatures needed in papermaking processes. There is already a wide variety of solar heat technologies available, varying in the type of solar collectors (size, temperature range, efficiency, price) and application of the heat in the industrial process. Most of them are in the pilot and demonstration phases. Further development of these systems is needed to increase energy and cost-efficiency.

Impact:
Onsite renewable energy production and use have a direct impact on CO_2 emission reduction. Looking at the area needed for the solar panels, it cannot be expected that the entire energy need of a paper mill can be provided with solar thermal. The potential reduction in CO_2 emission and energy costs will depend on the location (affecting climate, insulation, taxes, cost of living, available space etc.) and quality of the system (affecting performance, lifetime and cost).

Technology Readiness Level (TRL): TRL: 5-7, TRL target: 9		
Expected deliverables	Demonstration of the new technologies at the sites of the pulp and paper mills	
Timeline	Market penetration will take place until 2030	
Parties / Partners (countries / stakeholders / EU)	**Implementation financing / funding instruments**	**Indicative financing contribution**
European pulp and paper companies, Equipment suppliers, Research institutes	R&D funding for energy and fuels from pulp mill side streams (national, Horizon Europe) Funding for pilots and demo's and first implementation (e.g. Innovation Fund), European	R&D: €50 million, Several demos: €15 million each, First flagships: €30 million each

	financing instruments (EIB), Private equity and debt	

Gaps:
While innovative biorefinery technologies greatly improve the resource efficiency of pulp mills, the CO_2 emissions of pulp mills will not decrease. These mills are already CO_2 neutral. The CO_2 savings from biorefinery products will occur in sectors other than the investing sector. The current climate policy does not stimulate innovation to decrease the CO_2 emissions in other value chains. At the same time, customers are not stimulated to ask for products with a lower CO_2-footprint.
This also holds for biogas production and utilisation from external waste streams. Current incentives do not stimulate external organisations to share their renewable energy sources with others, even though these companies may use these energy sources more efficiently.
It is crucial to get a CO_2 calculation methodology that stimulates total system / chain efficiency so that savings in one part of the system do not lead to increased emissions elsewhere.

9.6.6 Activity 6.6 – Biomass as alternative feedstock

This fiche is shared between Chemicals and Pulp & Paper sectors due to the nature of the technology. Details are provided in Activity 4.5.

10 ANNEX 3: IWG MEMBERS AND CONTRIBUTORS TO THE IMPLEMENTATION PLAN REVISION

10.1 Composition of the Implementation Working Group 6

The official members Countries of the IWG6 are:

Austria (AT)
Belgium (BE)
Switzerland (CH)
Cyprus (CY)
Czech Republic (CZ)
Germany (DE)
Spain (ES)
Finland (FI)
France (FR)
Ireland (IE)
Italy (IT)
Latvia (LV)
The Netherlands (NL)
Norway (NO)
Poland (PL)
Portugal (PT)
Sweden (SE)
Slovakia (SK)
Turkey (TR)

Industry stakeholders participating in the IWG6 are listed below.

Table 10-1 Industry Stakeholders

A.SPIRE	Association - Sustainable Process Industry through Resource and Energy Efficiency
Baker Hughes	Baker Hughes
CEMBUREAU	European Cement Association
CO_2 Value	CO_2 Value Europe
CCSA	CCS Association
CEPI	Confederation of European Paper Industries
CEFIC	European Chemical Industry Council
COGEN Europe	European Association for the Promotion of Cogeneration
Delft University of Technology	Delft University of Technology
DHC+ / Euroheat & Power	The Technology Platform and Network for district energy, promoting sustainable heating and cooling in Europe and beyond
EHP	Euroheat & Power
EASE	European Association for Storage of Energy
EERA	European Energy Research Alliance
EGEC	EU Geothermal Energy Council
EU Turbines	European associations representing the turbine sector in Europe
ETN	European associations representing the turbine sector in Europe
Energieinstitut an der Johannes Kepler Universität Linz	Energieinstitut an der Johannes Kepler Universität Linz
ENTSOE	European Network of Transmission System Operators for Electricity
ENTSOG	European Network of Transmission System Operators for Gas
EUA	European University Association
Eurofer	European Confederation of Iron and Steel Industries
ESTEP	European Steel Technology Platform - Ultra Low CO_2 Steel consortium
FTP	Forest-based Technology Platform
Hydrogen Europe	Hydrogen Europe
FCH JU	Fuel Cell Hydrogen Joint Undertaking
KCORC	Knowledge Center on Organic Rankine Cycle technology
MAN Energy Solutions SE	MAN Energy Solutions SE
TU Dortmund	Technische Universität Dortmund

10.2 Country representatives and stakeholders involved with the update of the IP

DG ENER and the Secretariat would like to thank all who contributed to the revision of the IP. Including, the following stakeholders who provided material and feedback to be included in this document:

Table 10-2 Country representatives who provided feedback for the IP

Finland (FI) (chair)	The Netherlands (NL)
Austria (AT)	Portugal (PT)
Switzerland (CH)	Sweden (SE)
Spain (ES)	Turkey (TR)
Italy (IT)	

Table 10-3 Stakeholders who provided material and feedback for the IP

A.SPIRE – Association – Sustainable Process Industry through Resource and Energy Efficiency	EU Turbines – European associations representing the turbine sector in Europe
CEMBUREAU – European Cement Association	ETN – European associations representing the turbine sector in Europe
CEPI – Confederation of European Paper Industries	Eurofer – European Confederation of Iron and Steel Industry
CEFIC – European Chemical Industry Council	ESTEP – European Steel Technology Platform – Ultra Low CO_2 Steel consortium
ENTSOG – European Network of Transmission System Operators for Gas	TU Dortmund – Technische Universität Dortmund

Additionally, DG ENER and the Secretariat also extend thanks the following stakeholders who provided feedback on draft texts during the revision of the IP:

Table 10-4 Stakeholders who provided feedback for the IP

Baker Hughes	FCH JU - Fuel Cells and Hydrogen Joint Undertaking
CDTI - Centre for the Development of Industrial Technology (Spain)	KCORC - Knowledge Centre on Organic Rankine Cycle technology
CIRCE – Research Centre for Energy Resources and Consumption	JRC - Joint Research Centre
ENEA - Italian National Agency for New Technologies, Energy and Sustainable Economic Development (Italy)	MAN Energy Solutions SE
Energieinstitut an der Johannes Kepler Universität Linz	Ministry of Economic Affairs (Finland)
EERA - European Energy Research Alliance	SFOE - Swiss Federal Office of Energy (Switzerland)
EGEC - EU Geothermal	Siemens Energy AG
Euroheat & Power	SWEA – Swedish Energy Agency (Sweden)
ENTSO-G - European Network of Transmission System Operators for Gas.	TU Delft - Delft University of Technology