

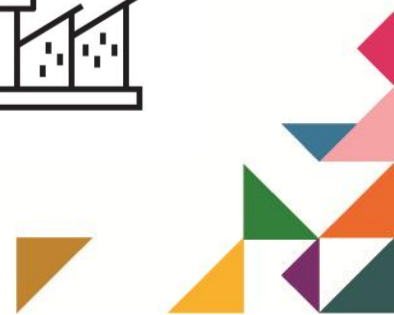


Strategic Energy Technology Plan

Implementation Working Group on Sustainable and Efficient Energy Use in Industry

Thematic Vision on Sustainable and Efficient Energy Use in Industry

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Executive Summary

The IWG on Sustainable and Efficient Energy Use in Industry (IWG-Industry) supports the transformation of Europe's energy-intensive industries towards climate neutrality by 2050, while enhancing its competitiveness. Bringing together SET Plan countries, industry representatives and research actors, the group promotes coordinated action to accelerate the development and deployment of low-carbon technologies across industrial sectors.

By 2030, the IWG-Industry aims to enable the first large-scale deployment of low-carbon technologies across energy-intensive industries (EIs). Key decarbonisation pathways – including electrification, hydrogen-based processes, circularity, and carbon capture, utilisation and storage (CCUS) – are expected to progress significantly towards industrial deployment, with many technologies reaching advanced technological maturity (TRL 7–9) and early commercial operation. At the same time, several breakthrough technologies will remain at pilot or demonstration stage, requiring further validation and scale-up beyond 2030. This period will deliver measurable emissions reductions aligned with EU climate targets, enabled by the emergence of lead markets for low-carbon products, and initial deployment of enabling infrastructures for near-zero-carbon electricity and hydrogen, as well as CO₂ transport and storage infrastructure. However, deployment will remain uneven, constrained by high costs, infrastructure gaps and regulatory complexity.

By 2040, these technologies are expected to be widely deployed across industrial sectors, supported by expanded hydrogen and CO₂ infrastructure, greater electrification and digitalisation of industrial processes, and more mature circular economy approaches. Market uptake of low-carbon products will increase as policy frameworks stabilise and technology costs decline, although progress will vary across sectors depending on readiness and infrastructure availability.

By 2050, the IWG-Industry envisions a fully transformed industrial system achieving climate neutrality. This will be enabled by electrified and hydrogen-based production routes, circular material flows, and targeted use of CCUS for residual emissions, ideally carbon of biological origin, i.e. biogas, biomethane, or other biofuels. Industrial systems will operate as integrated, flexible and digitalised ecosystems optimising energy, material and CO₂ flows across value chains, while maintaining Europe's industrial competitiveness through strong clean technology manufacturing capacity and functioning markets for low-carbon products.

Achieving this vision requires stable policy frameworks, development of lead markets, and coordinated infrastructure planning for electricity, hydrogen and CO₂. Key challenges include scaling up from demonstration to deployment, reducing costs, ensuring access to affordable low-carbon energy, and strengthening European supply chains, alongside reducing regulatory fragmentation and filling skills gaps.

The IWG-Industry supports coordinated actions across sectors, including joint R&I priorities, alignment of national programmes and knowledge exchange, feeding into the Strategic Research and Innovation Agenda (SRIA).

For the 2028–2034 period, priority areas include: (i) industrial electrification and hydrogen-based technologies, including high-temperature heat applications, (ii) carbon management and CO₂ infrastructure, and (iii) circularity and alternative carbon feedstocks, to accelerate scale-up and industrial deployment.

Overall, the IWG-Industry provides a coordinated framework to support industrial decarbonisation while reinforcing competitiveness, resilience and Europe's strategic autonomy.

1. Introduction

1.1. Policy context and role of the IWG-Industry

The European policy framework for industrial decarbonisation is anchored in the European Green Deal and the European Climate Law, which establish the objective of climate neutrality by 2050, with intermediate greenhouse gas emission reduction targets of at least 55% by 2030 and 90% by 2040 compared to 1990 levels.¹ More recently, EU industrial policy has increasingly combined decarbonisation objectives with competitiveness, resilience and industrial leadership. This approach is reflected in initiatives such as the Clean Industrial Deal, the Competitiveness Compass, the Net-Zero Industry Act and the Industrial Accelerator Act, which seek to accelerate the deployment of clean technologies, strengthen European manufacturing capacity and create favourable market conditions for low-carbon products. At the same time, instruments such as the EU Emissions Trading System, green public procurement and product standards support investment and market uptake.

Within this context, energy-intensive industries are central to achieving climate neutrality while preserving Europe's industrial base and strategic autonomy. The IWG-Industry contributes to the implementation of the SET Plan by supporting the development, demonstration and deployment of technologies and system solutions that enable the transformation of EIs towards climate neutrality and industrial competitiveness.

1.2. Objective of the Thematic Vision

This Thematic Vision provides a framework for the transformation of energy-intensive industries, identifying key technological pathways, research and innovation priorities, and enabling conditions required to achieve climate neutrality while strengthening industrial competitiveness. The Vision covers **five industrial sectors** (iron and steel, cement, chemicals, pulp and paper, and aluminium) together with **two cross-cutting areas** (heating and cooling, and systems). These sectors face common challenges, including process-related emissions, long investment cycles, infrastructure requirements and the integration of low-carbon electricity, hydrogen, circular feedstocks and CO₂ management solutions. Beyond emissions reduction, the Vision addresses technology performance, system integration, scalability and industrial deployment. The pathways outlined here will be further translated into research and innovation priorities and activity fiches within the Strategic Research and Innovation Agenda (SRIA).

1.3. Key developments, drivers and barriers

The transformation of energy-intensive industries is accelerating, driven by stronger policy frameworks, technological progress and growing emphasis on industrial competitiveness. **Significant advances** are being made in industrial heating and cooling, electrification, waste heat recovery, hydrogen integration, circular feedstocks, CCUS, digitalisation and industrial symbiosis. At the same time, increasing interactions between industrial processes, energy systems and infrastructure are reinforcing the importance of **system-level approaches**.

Nevertheless, decarbonisation pathways differ across sectors. In **iron and steel**, the transition is characterised by the emergence of hydrogen-based production routes enabling direct emissions avoidance, combined with increased circularity through scrap use, while CCUS is being explored for residual emissions, ideally carbon of biological origin, i.e. biogas, biomethane, or other biofuels. The **chemical sector** presents a more diversified landscape, with the integration of alternative energy carriers and sources (including electrification, hydrogen, steam and heat from Small Modular (nuclear) Reactors), alternative hydrogen production, and the utilisation circular carbon feedstocks (waste, biomass, captured CO₂) progressing in parallel, alongside increasing efforts in process optimisation and system integration, and the deployment of carbon capture storage (CCS), although large-scale integration remains limited. In **pulp and paper**, progress is relatively advanced, driven by the integration of alternative energy carriers (including biomass, biogas, hydrogen and renewable heat sources) and ongoing efficiency improvements through process optimisation and modular electrification. Additional developments include emerging waterless paper production concepts and increasing deployment of bio-CCUS, although further progress is needed in process electrification and system integration. In **aluminium**, the transition is already highly electrified and supported by strong recycling rates, with further decarbonisation relying on the deployment of breakthrough technologies such as inert anodes, hydrogen-based furnaces and CCS for residual emissions, although these solutions remain at different stages of maturity.

Despite these differences, **common barriers** emerge across all sectors. A critical bottleneck lies in bridging the “first-of-a-kind” (FOAK) and **scale-up gap**, where technologies that have reached demonstration stage struggle to achieve reliable and cost-competitive operation under real industrial conditions. This is closely linked to high capital intensity, investment risk, and the lack of proven business cases. In parallel, the availability of **enabling infrastructure**—including electricity grids, hydrogen networks and CO₂ transport and storage systems—remains a key constraint, requiring long-term planning and coordination across sectors and regions. Market-related barriers further limit deployment, as the absence of sufficiently developed lead markets weakens investment signals for low-carbon industrial products. Additional constraints arise from the availability of **clean technology supply chains** and manufacturing capacity in Europe, particularly for key components such as electrolyzers, electrified heat technologies and CO₂ capture systems. Increasing system complexity—driven by the integration of multiple energy carriers, processes and infrastructures—also creates operational challenges, especially at industrial site and cluster level. Finally, fragmented **regulatory and permitting frameworks** continue to delay project implementation. These barriers are consistently reflected in roadmaps and strategic documents developed by European industry associations acting as activity leaders within the IWG-Industry.² Addressing them requires coordinated action across EU policies, SET Plan countries, industrial stakeholders and other SET Plan Implementation Working Groups.

1.4. Task Force recommendation reflections

The IWG-Industry work programme is closely aligned with the five SET Plan Task Force priorities. **Circularity and digitalisation** are embedded across all industrial transition pathways, supporting resource efficiency, process optimisation and system integration. **Market creation measures**, including regulatory frameworks and certification schemes, are essential to accelerate the deployment of low-carbon technologies. At the same time, **market protection measures** addressing competition from imports with lower environmental standards should also be considered to safeguard the competitiveness of European industry during the transition. **Skills development** is needed to support workforce adaptation, while **societal considerations** remain central to ensuring that industrial decarbonisation strengthens competitiveness, supports quality employment and maintains public acceptance.

2. Vision and targets

2.1. Short-term (2030)

By 2030, the IWG-Industry supports the coordinated deployment of industrial decarbonisation solutions across seven complementary domains, covering **five energy-intensive sectors** (iron and steel, cement, chemicals, pulp and paper, and aluminium) and **two transversal areas** (industrial heating and cooling, and system-level integration).

Taken together, these developments aim to enable **emissions reductions** across energy-intensive industries by 2030 to reach the overall EU target of reducing net greenhouse gas emissions by at least 55% by 2030 (compared to 1990 levels). Across all sectors, demonstration activities at TRL 6–7 should be guided by total cost of ownership (TCO) considerations, ensuring that technologies progress towards commercial deployment through solutions that are both technically effective and economically viable.

HEATING AND COOLING

A key contribution will come from **heat upgrading** technologies, enabling the conversion of low-grade excess heat into higher temperature heat for reuse within industrial processes. By 2030, solutions are expected to reach TRL 7 for temperatures up to 200–250°C and TRL 6 for higher temperatures, delivering initial improvements in energy efficiency and enabling early deployment across industrial sites.

In parallel, waste heat recovery and conversion technologies will advance across different temperature ranges. For **high-temperature waste heat** (>300°C), cost-effective solutions are expected to reach TRL 7, enabling early deployment in energy-intensive industries. Under these conditions, up to 20% of the available high-temperature waste heat could be converted into useful energy (mechanical or electrical). **Medium-temperature solutions** (120–350°C) will progress from demonstration to early industrial application, relative to 2025 performance levels. This is expected to result in approximately a 5% improvement in conversion efficiency and a 10% reduction in **levelised cost** of energy (LCOE), together with the use of improved non-toxic working fluids and around 10% reductions in system footprint and capital cost, depending on the specific temperature range and application. In contrast, **low-temperature recovery technologies** (<120°C) will remain at earlier stages of development, targeting the recovery of around 5% of low-temperature waste heat relative to 2025 baseline conditions, with validation and pilot-scale deployment.

Further integration of **waste and renewable heat for cold generation** will support the decarbonisation of cooling demand, with technologies reaching demonstration stage (TRL 7) and early deployment in cooling-intensive sectors.

At system level, **flexible heating systems, hybrid plants and polygeneration solutions** will begin to enable the integration of **thermal and electrical renewable energy sources, waste heat and storage** into industrial energy systems. By 2030, these technologies are expected to reach demonstration stage (TRL 7), with early deployment in industrial clusters and frontrunner sites.

In addition, **high-temperature electric heating** (power-to-heat) for industrial applications (typically above 500°C) will begin to electrify industrial heat demand, with MW-scale solutions reaching demonstration stage and early deployment in energy-intensive industries.

SYSTEMS

A central contribution will come from the deployment of **industrial symbiosis**, enabling cross-sector integration and shared infrastructure. By 2030, solutions including local logistics systems and the integration of data centres as providers of recoverable waste heat are expected to reduce combined energy consumption by around 10–20%, with approximately 15 full-scale industrial symbiosis hubs operational across Europe.

In parallel, the **integration of non-conventional energy sources**, including geothermal and solar thermal, biomass, waste-derived energy and CO₂ utilisation, will increase, reaching around 20% share in the energy mix. Digital systems supporting the management of integrated heating and cooling networks – including the coupling of industrial facilities and data centres – will become available, alongside improvements in CO₂ capture and purification processes to reduce their energy use. These developments will support the deployment of integrated energy systems across industrial sites. Industrial processes will also increasingly contribute to **energy system flexibility** through demand-side management, load shifting and the integration of thermal and electrical storage, enabling a better alignment of industrial energy demand with variable renewable electricity generation. **Digitalisation** will enable improved control, automation and optimisation of industrial processes, with process control solutions expected to be implemented in around 20% of industrial plants by 2030, supporting early-to-mid adoption across sectors.

At the same time, **knowledge exchange, training and capacity building** will play a critical role in enabling the transition, with the development of new curricula aligned with SET Plan needs and the implementation of tailored in-company training programmes. Initial deployment of these frameworks is expected across Member States, supporting workforce readiness for industrial transformation.

IRON AND STEEL

By 2030, the European iron and steel sector is expected to achieve a substantial reduction in **greenhouse gas emissions**, targeting a decrease of around 30% compared to 2018 levels (equivalent to approximately 55% compared to 1990).

This progress will be underpinned by the advancement of three complementary decarbonisation pathways: Carbon Direct Avoidance (CDA), Circular Economy, and Smart Carbon Usage via CCUS, all progressing towards near-commercial maturity by 2030.

CDA will focus on reducing direct emissions through the substitution of fossil carbon, notably via **hydrogen-based direct reduced iron** combined with electric arc furnaces (H₂-DRI-EAF) in primary steelmaking routes (iron ore-based production), while secondary steel routes based on scrap and electric arc furnaces are expected to decarbonise mainly through electrification and efficiency improvements, as well as through the use of alternative low-carbon carbon sources such as biogas and biochar during transition phases. By 2030, hydrogen-based reduction technologies are expected to reach TRL 8 demonstration stage, achieving iron oxide reduction rates above 90% and replacing more than 50% of the natural gas input with hydrogen in DRI processes. In parallel, early electrolytic reduction technologies are expected to demonstrate reduction efficiencies above 85%. Such efficiencies would correspond to electricity consumption levels of approximately 2.7–3.0 MWh/t steel. These technologies are expected to contribute to total emissions reductions at sector level of around 6% in 2030 compared to 2018 levels and energy savings of approximately 15%.

Circular Economy approaches will aim to reduce primary iron demand through **increased scrap utilisation**, improved material efficiency and enhanced recovery of secondary raw materials,

primarily within secondary steel production routes (electric arc furnace-based steelmaking), while also contributing to reduced demand for primary steel inputs. By 2030, scrap and residue recycling rates are expected to exceed 85%, supported by the development of advanced scrap pre-treatment, cleaning and scrap yard management solutions enabling the increased use of low-quality post-consumer scrap in higher-quality steel production. In parallel, the recovery of low-quality scrap and Fe-bearing residues is expected to increase by at least 50% compared to current practices, while progressively replacing solid pig iron with post-consumer scrap. These circular metallurgy solutions are expected to reach TRL 8 and contribute to total emissions reductions at sector level of around 12% in 2030 compared to 2018 levels.

In parallel, **Smart Carbon Usage via CCUS** will address remaining process emissions through CO₂ capture, utilisation and storage, particularly in integrated steelmaking routes (blast furnace–basic oxygen furnace and other primary steel production processes). By 2030, CCUS technologies are expected to reach early industrial deployment in dedicated process streams, achieving capture rates above 95% in key applications and enabling the conversion of captured CO₂ into chemicals, fuels and materials with carbon utilisation efficiencies exceeding 65%. These technologies are expected to reach TRL 8 in key applications and contribute to total emissions reductions at sector level of around 5% in 2030 compared to 2018 levels.

At least four **large-scale demonstration projects** are expected to be operational across Europe, supported by the industrial validation of smart electrification and digital process optimisation solutions.

From a market perspective, early **demand for low-carbon steel** is expected to materialise, with uptake driven by lead markets and policy frameworks. In this context, the proposed Industrial Accelerator Act introduces a minimum 25% requirement for low-carbon steel in public procurement, reinforcing early demand signals from the public sector. However, market uptake will remain at an early stage, with cost and infrastructure constraints remaining key barriers.

This market development will need to be supported by a parallel **scale-up of enabling manufacturing and infrastructure capacities** for low-carbon steel technologies. By 2030, at least 30% of EU primary steel capacity is expected to be converted or under conversion to low-carbon routes (including hydrogen-based DRI, EAF expansion and CCUS), alongside the installation of approximately ≥40 Mt/year of low-carbon steel production capacity. In parallel, European electrolyser manufacturing capacity is expected to scale in the order of ~5–7 Mt H₂/year, depending on project deployment rates and enabling conditions, while CO₂ transport and storage infrastructure is expected to become operational in major industrial steel clusters, enabling the deployment of CCUS-based routes and hydrogen-based production systems.

CEMENT

By 2030, the European cement sector is expected to achieve significant reductions in **greenhouse gas emissions**, targeting approximately a 37% decrease in gross CO₂ emissions and around a 50% reduction in value chain emissions compared to 1990 levels. This progress will be driven by the combined deployment of fuel switching, electrification of selected high-temperature processes, material efficiency improvements, clinker reduction strategies, and early-stage carbon management technologies.

A major contribution will come from the increased use of alternative fuels, progressively replacing fossil fuels with waste-derived and biomass-based sources. Starting from a sector average of approximately 53% alternative fuel use in 2021, alternative fuels are expected to represent around

60% of total fuel use by 2030,³ including approximately 30% biomass-based waste, significantly reducing combustion-related emissions in clinker production. This transition will vary across Member States and will depend on technical feasibility, regulatory frameworks and feedstock availability, which may constrain the pace of deployment in certain national contexts.

In parallel, **alternative raw materials**, clinker substitution and circularity measures will reduce process emissions through improved material efficiency and the integration of decarbonised inputs, delivering around a 3.5% reduction in process CO₂ emissions.

Further reductions will be achieved through **clinker innovation and optimisation**, including new cement chemistries and reduced clinker content. These measures are expected to lower process emissions by around 2% supported by the early deployment of innovative clinker types and reduce the clinker-to-cement ratio to approximately 74%, compared to 77% in 2021. Complementary improvements in concrete mix design and admixtures will also reduce cement demand in downstream applications by around 5%, enhancing overall material efficiency. These optimised concrete solutions will be progressively adopted in selected construction segments, particularly in public infrastructure and low-carbon building projects where procurement criteria enable early uptake.

At the production level, **energy efficiency** improvements will contribute to further emissions reductions, with an expected 4% improvement in **thermal efficiency** across cement manufacturing processes. In addition, electrical efficiency measures, including **waste heat to power** systems, are expected to cover up to 20% of the present cement plant electricity demand. Further long-term emissions reduction potential is associated with emerging **electrification** technologies for high-temperature processes, such as electrical heating, plasma and solar-assisted calcination, which remain at early stages of development and could significantly reduce fuel-related CO₂ emissions when powered by renewable electricity.

CCUS technologies will start to emerge through pilot and demonstration projects, although deployment will remain limited at this stage and will depend on the development of transport and storage infrastructure as well as enabling regulatory frameworks. In addition, early-stage **recarbonation and mineralisation** processes will begin to be deployed, enabling partial CO₂ uptake within cement-based materials.

From a **market perspective**, low-carbon cement and concrete solutions are expected to gain traction in selected applications, driven by increasing demand for sustainable construction materials and early policy incentives. However, broader market uptake will remain at an early stage, with cost competitiveness, standardisation and regulatory alignment continuing to represent key barriers.

PULP AND PAPER

By 2030, the European pulp and paper sector is expected to achieve significant progress towards deep decarbonisation while increasing sectoral value creation.

A central pathway will be the integration of **alternative energy carriers and sources**, aimed at decarbonising energy-intensive processes using electricity, alternative low-carbon heat and energy sources, small modular nuclear reactors (SMRs), and sustainable biomass for heat and steam generation. By 2030, this will include the demonstration of **electrification** of key processes and the alternative fuel and heat sources, with partial uptake already visible in selected production lines.

In parallel, breakthrough approaches such as **paper making without water evaporation** will target the elimination of energy-intensive drying processes. These technologies are expected to reach

piloting and demonstration stages in industrial settings by 2030, with deployment remaining at pilot scale due to technological and integration challenges.

Complementary innovations in **mild and efficient pulping** technologies will reduce both energy and chemical intensity in pulping processes. These solutions are expected to be demonstrated by 2030, with deployment remaining at pilot scale as industrial validation progresses.

At the site level, **onsite renewable energy** conversion will contribute to increasing energy self-sufficiency through the integration of innovative renewable energy technologies. By 2030, these systems will be demonstrated and implemented at early stage, with adoption concentrated in frontrunner plants where conditions enable integration.

In addition, **bio-CCUS** will begin to address residual emissions through the capture, utilisation and storage of biogenic CO₂. These technologies are expected to be piloted in industrial settings by 2030, with limited deployment reflecting the early stage of infrastructure and regulatory development.

Beyond emissions reduction, the sector will also advance bio-based **product diversification**, increasing value creation through the development of new products derived from forest biomass. By 2030, continuous development, demonstration and early implementation of these products will support a gradual increase in their contribution to sector turnover, from current levels of around 3%.

From a **market perspective**, the uptake of low-carbon and bio-based solutions will begin to emerge across selected segments, driven by demand for sustainable materials, circular economy policies, and innovation in bio-based value chains. However, market penetration will remain at an early stage, with deployment largely concentrated in pilot projects, demonstration plants, and frontrunner industrial sites.

CHEMICAL

NB: This information is provisional and will be subject to further review and validation during the preparation of the SRIA.

By 2030, the European chemical sector (NACE Rev. 2 Code 20) is expected to make progress in reducing greenhouse gas emissions through the development, demonstration and early implementation of key technologies, focusing on resource and energy efficiency, electrification where possible, and the increased use of circular carbon feedstocks. Progress will depend on enabling conditions such as access to cost-competitive low-carbon energy, circular carbon feedstock, infrastructure and supportive policy frameworks.

A major contribution will come from process optimisation (e.g. waste heat upgrade), the integration of **alternative energy carriers and sources**, including the **electrification** of chemical processes through indirect (e.g. power-to-heat) and direct technologies (e.g. plasma, electrochemical processes), which will reach demonstration and early industrial deployment in selected applications. In parallel, the use of low-carbon **hydrogen** as an energy carrier will begin to be explored, addressing technical challenges related to retrofitting existing installations, while the development of SMRs will progress for heat and steam generation.

In addition, **alternative hydrogen production** routes will advance, focusing on improving electrolysis technologies and developing processes such as methane pyrolysis, remaining at development and demonstration stage.

The transition towards **circular carbon feedstocks**, including waste, captured CO₂ and biomass, will represent a key pathway to reduce reliance on fossil-based inputs. Chemical recycling of waste will

focus on addressing feedstock contamination and improving process efficiency and scalability, while the use of captured CO₂ will require improvements in capture, purification and conversion processes. Biomass-based pathways will also progress through the development and demonstration of new conversion and separation technologies.⁴

However, **deployment** across all these routes will remain constrained by costs, access to clean energy and alternative carbon feedstocks, related infrastructure, policy framework and regulatory conditions.

Further improvements will be achieved through **process optimisation** and integration, enhancing efficiency and enabling better integration of new technologies into existing and redesigned production systems, with implementation taking place where technically and economically feasible.

ALUMINIUM

By 2030, the European aluminium sector is expected to achieve significant progress towards deep decarbonisation across the value chain, targeting a reduction of **greenhouse gas emissions** by 36% compared to 2021 levels (from approximately 24 MtCO_{2e} to around 15 MtCO_{2e}).

A major contribution will come from the **electrification of thermal processes**, replacing fossil-based heat with electric solutions across alumina refining, recycling and remelting operations. By 2030, industrial pilots and early commercial deployment of electric boilers and mechanical vapour recompression (MVR) for digestion are expected to reach TRL 8–9 in alumina refining, while electric calciners will progress through pilot and first-of-a-kind demonstration stages (TRL 6–7). In parallel, electric remelting and holding furnaces for recycling and downstream operations will be demonstrated at pilot scale (TRL 6–7), with approximately 15–25% of downstream furnaces electrified and early adoption emerging in digestion and calcination processes where technically and economically feasible.

In parallel, the conversion to low-carbon **hydrogen furnaces** will begin to address high-temperature applications where direct electrification remains challenging, particularly in recycling, downstream operations and selected upstream thermal processes. By 2030, industrial-scale demonstrations of hydrogen-fired furnaces are expected to reach TRL 7, including retrofitting of existing furnaces and validation of hydrogen-ready designs. Development efforts will focus on combustion challenges such as NO_x emissions, furnace material compatibility and melt quality. Around 5–10% of new high-temperature furnace installations are expected to be hydrogen-ready by 2030, although operational hydrogen use will remain limited due to cost and infrastructure constraints.

Breakthrough developments in low-carbon **aluminium electrolysis** will focus on eliminating process emissions from primary aluminium production through **inert anodes** and alternative technologies such as **carbo-chlorination**. By 2030, inert anodes are expected to reach TRL 5–6 and carbo-chlorination TRL 4–6, with pilot-scale demonstrations in industrial smelters focusing on safety protocols and integration with existing smelter infrastructure and renewable electricity supply. Deployment will remain limited to pilot cells and demonstration potlines, representing less than 5% of global production capacity.

At system level, **flexible electricity systems** will start to enable primary aluminium production to operate as a more flexible and demand-responsive industrial asset aligned with variable renewable electricity supply. By 2030, smart load management solutions (TRL 5–7) will be piloted, with early adoption at selected demonstration sites.

Further emissions reductions will be supported by advanced scrap sorting and pre-treatment technologies, strengthening **aluminium circularity**, improving scrap quality and supporting greater

resource autonomy. By 2030, sensor-based sorting technologies (LIBS, XRT, XRF) are expected to reach TRL 8–9 with early industrial deployment across pilot recycling facilities, while melt refinement and purification technologies will remain at TRL 5–7.

Carbon capture and storage (CCS) will begin to be explored as a complementary solution to address residual process and combustion emissions in hard-to-abate segments where electrification or low-carbon fuels are not technically or economically feasible. By 2030, pilot plants at TRL 4–7 will focus on primary production and selected thermal processes such as alumina refining, calcination and remelting, alongside feasibility studies, integration assessments and early interfaces with regional CO₂ transport and storage infrastructure. Deployment is expected to remain very limited, mainly consisting of pilot installations and demonstration projects.

Complementary improvements in **waste heat recovery** and **energy efficiency** will contribute to overall emissions reductions across both upstream and downstream segments of the aluminium value chain. By 2030, pilot-scale waste heat recovery systems (TRL 6–8), including preheaters and organic Rankine cycle (ORC) units, are expected to be deployed in early adopter plants, representing less than 10% of installations. These measures will support improved energy performance and greater integration of low-carbon production systems across the sector.

2.2. Medium-term (2040)

While significant progress has been made in defining sector-specific targets for 2030 and long-term climate neutrality objectives for 2050, the level of detail and maturity of 2040 milestones varies across sectors. As a result, detailed 2040 projections are included only for those sectors where sufficiently robust and validated data were available at the time of drafting. Across all sectors, the large-scale deployment of electrified industrial processes will require substantial expansion and reinforcement of electricity infrastructure. Reliable, high-capacity electricity networks, together with adequate generation, storage and system integration solutions, will be essential to ensure secure and cost-competitive power supply throughout the year and to accommodate increasingly dynamic industrial demand patterns associated with flexible and electrified production processes.

HEATING AND COOLING

By 2040, heating and cooling technologies are expected to be **widely deployed** across industrial sectors, supporting significant progress in decarbonisation through integrated, efficient and flexible thermal energy systems. Building on the demonstration and early deployment achieved by 2030, this period will be characterised by the scaling-up of key technologies and increasing market uptake across industrial applications.

Across most technology pathways, systems are expected to reach high levels of maturity (around TRL 8), delivering **efficiency improvements** of approximately +5% and **reductions in LCOE** of around 10% compared to 2030, supported by the integration of hybrid solutions combining heat recovery, electrification and storage.

IRON AND STEEL

By 2040, the European iron and steel sector is expected to achieve deep emissions reductions, building on the decarbonisation pathways established by 2030 and scaling them to full industrial deployment across Europe.

Demand for low-carbon steel will be widely established, with up to 60% of EU steel consumption sourced from near-zero emission production. In parallel, the green steel **price premium** is expected

to decline significantly due to economies of scale and supportive policy frameworks, while circularity and life-cycle carbon accounting become systematically integrated across the value chain.

At production level, **electrification** is expected to play an increasing role, covering more than 60% **of thermal demand** in both primary and secondary steel production. At the same time, **digitalisation** will enable further optimisation of industrial processes, with mature digital twins and AI-driven process optimisation deployed across at least 75% of plants.

The **three decarbonisation pathways** introduced in 2030 will have evolved from early industrial deployment to fully commercial and **widely deployed** solutions.

Carbon Direct Avoidance technologies are expected to reach full maturity (TRL 9) by 2040 supported by large-scale **hydrogen** availability and extensive **electrification** in primary steel routes, while secondary steel routes will be largely decarbonised through scrap-based electric arc furnace optimisation. **Circular Economy** approaches will expand significantly beyond the levels achieved by 2030, with **higher scrap** utilisation rates, optimised material efficiency, and large-scale valorisation of industrial residues, forming the dominant decarbonisation lever in secondary steel production routes.

Smart Carbon Usage via CCUS, initially deployed at pilot and early industrial scale by 2030, will be scaled up through fully operational industrial clusters. Deployment will focus on remaining carbon-intensive assets in integrated steelmaking, ensuring that residual emissions are effectively captured, utilised, or permanently stored in primary steel production routes.

In parallel, complementary **breakthrough technologies** such as plasma smelting and advanced electrification will reach commercial availability. Electrification could account for up to ~60% of thermal energy demand, while digitalisation—through AI-driven optimisation and digital twins—will be widely implemented across the majority of installations.

From an industrial perspective, at least 75% of **EU steel production** will be based on low-carbon routes. This transformation will be enabled by large-scale hydrogen infrastructure and CO₂ transport and storage networks, as well as by a strengthened European equipment supply chain (furnaces, electrolyzers, digital systems, CCUS).

PULP AND PAPER

By 2035-2040, the pulp and paper sector is expected to transition from pilot and demonstration phases towards **early commercial deployment** of the decarbonisation pathways identified for 2030. This period will be characterised by the scaling of **electrification**, **alternative energy** integration, **process optimisation** and **circular solutions** across industrial sites.

Several technologies—including **paper making without water evaporation** and **mild pulping processes**—are expected to reach first commercial operations, while modular electrification and optimisation solutions will see increasing adoption across 5-25% of production systems. In parallel, **onsite renewable energy** integration will expand across energy-intensive sites, supporting greater energy self-sufficiency. Alternative **low-carbon heat sources** will progressively complement direct electrification solutions in selected high-temperature applications where electrification alone may not be technically optimal. **Bio-CCUS** will progress to large-scale demonstration, with early deployment in selected industrial clusters where enabling infrastructure is available. At the same time, **bio-based alternative products** will gain increasing market presence.

ALUMINIUM

By 2040, the European aluminium sector is expected to significantly advance its decarbonisation pathway, building on the technologies and solutions deployed by 2030 and moving towards large-scale industrial adoption across the value chain.

The **electrification of thermal processes** will reach high levels of maturity, with electric boilers and mechanical vapour recompression (MVR) systems becoming fully competitive, while electric calciners and high-temperature electric furnaces approach broad commercial availability. This is expected to enable electrification of approximately 40–50% of digestion and calcination processes where technically feasible, alongside 50–70% electrification of downstream furnaces.

The use of low-carbon **hydrogen in high-temperature furnaces** will also expand, particularly in recycling and downstream operations where electrification remains more challenging. By 2040, hydrogen burners and dual-fuel furnace systems are expected to reach full commercial maturity (TRL 9), supported by the establishment of regional hydrogen clusters and supply networks. Market uptake is expected to reach approximately 20–30% of high-temperature units, depending on low-carbon hydrogen availability and cost competitiveness.

In parallel, **low-carbon aluminium electrolysis** technologies will approach commercial readiness, supported by the development of industrial supply chains and integration into existing smelter infrastructure. By 2040, around 20% of smelter potlines are expected to adopt inert anode technology, significantly reducing process-related emissions, while carbo-chlorination technologies remain limited to early commercial plants and new production capacity.

At system level, **flexible electricity systems** will be deployed at larger scale, with advanced control systems, energy storage integration and hybrid energy solutions improving operational flexibility and resilience. These solutions are expected to support alignment with renewable electricity supply across approximately 40% of EU smelting capacity, particularly in regions with high renewable penetration and adequate grid infrastructure.

Advanced scrap sorting and pre-treatment systems will become increasingly integrated and technically optimised across Europe, supporting broad adoption of high-quality recycling streams and strengthening **aluminium circularity** and resource autonomy across the sector.

Carbon capture and storage (CCS) technologies will progressively reach industrial readiness, with deployment focused on hard-to-abate segments and residual process emissions where electrification or low-carbon fuels are not sufficient or technically feasible. By 2040, CCS systems are expected to be integrated into regional CO₂ transport and storage hubs, supported by enabling regulatory frameworks and cross-sector infrastructure, with targeted deployment addressing approximately 10–20% of residual emissions.

In addition, **waste heat recovery** and **energy efficiency** solutions will be deployed more widely across the aluminium value chain. System-wide waste heat recovery solutions, advanced controls and improved energy management systems are expected to reach TRL 8–9, enabling deployment in approximately 40–50% of plants where technically and economically feasible.

2.3. Long-term (2050)

HEATING & COOLING

By 2050, industrial heating and cooling systems will be widely deployed as standard industrial practice. These carbon-neutral systems will enable highly efficient and circular thermal energy use across sectors, contributing to reduced production emissions, lower use of critical raw materials, increased reuse of end-of-life materials, and a +25% extension of system lifetime.

Waste and renewable heat integration for cooling applications will contribute to the decarbonisation of cooling demand, addressing approximately 4.5% of global GHG emissions from cooling and enabling up to 15% reduction in electricity demand for cooling processes, through the large-scale substitution of conventional cooling systems with waste-heat and renewable-driven alternatives.

Flexible heating systems and hybrid plants will be fully deployed across industrial clusters, enabling the integration of thermal and electrical renewable energy sources, storage and waste heat recovery.

Heat upgrading and waste heat recovery technologies will further reinforce these gains, enabling waste heat recovery and conversion to power with efficiencies of up to ~20% for high-temperature heat, ~10% for medium-temperature heat, and 1–10% for low-temperature heat streams, depending on process conditions.

SYSTEMS

By 2050, industrial systems across Europe are expected to operate as fully interconnected and optimised ecosystems through the large-scale deployment of industrial symbiosis, digitalisation, non-conventional energy integration and advanced workforce transformation. Industrial symbiosis networks will be widely established, with more than 200 **industrial symbiosis hubs** deployed across Europe, enabling large-scale optimisation of energy, material and CO₂ flows between sectors and regions, with industrial symbiosis fully embedded as a structural component of European industrial systems, delivering systemic efficiency gains and enabling deep decarbonisation across value chains.

Digitalisation will reach full deployment across industrial plants, enabling 100% implementation of advanced process control, automation and real-time optimisation systems, supporting efficiency gains and improved integration of complex industrial energy and material systems. In parallel, **non-conventional energy sources** – including geothermal, solar thermal, biomass, waste-derived energy and CO₂ utilisation systems – will be fully integrated into industrial energy and carbon management systems, becoming a standard component of decarbonised industrial processes. Education, training and upskilling **frameworks will be fully operational across countries, ensuring continuous** workforce adaptation to industrial transformation and supporting the deployment of new digital, energy and process technologies at scale.

IRON AND STEEL

By 2050, the European iron and steel sector is expected to achieve **climate neutrality**. Net-zero production routes will be fully commercialised and universally deployed across both primary and secondary steelmaking, with fossil carbon largely eliminated. This transformation will deliver a total system CO₂ emissions reduction of approximately 85–95% (~123–138 Mt CO₂eq/year) compared to 1990 levels.

Carbon Direct Avoidance will account for approximately 70–75% of total emissions reductions, enabling hydrogen- and electricity-based steelmaking to replace conventional fossil-based production at scale in primary steel routes, while secondary steel routes will contribute through fully electrified and highly efficient scrap-based production systems. **Circular economy** measures will contribute around 30–35% of total abatement, driven by maximised **scrap utilisation**, improved material efficiency and a structurally reduced demand for primary iron in secondary steelmaking as the dominant production route. **Carbon Capture, Utilisation and Storage (CCUS)** will address approximately 20% of remaining emissions, focusing on residual process emissions that cannot be otherwise avoided and being integrated within remaining carbon-intensive production routes (primarily in residual primary steel processes).

CEMENT

By 2050, the European cement sector is expected to achieve **net-zero emissions** across the value chain through the full deployment of fuel switching, clinker optimisation, electrification of selected high-temperature processes, material efficiency and large-scale carbon capture, utilisation and storage.

Alternative fuels will reach around 95% substitution (including ~50% biomass), effectively eliminating fossil fuel use in clinker production. **Clinker reduction** and innovation will be fully embedded, reducing the clinker-to-cement ratio to around 60% and delivering approximately 5% reduction in process CO₂ emissions, while **material efficiency** measures will reduce cement demand in concrete by up to 15%. **Thermal efficiency** will improve by around 14% compared to 1990 levels through process optimisation and heat integration. **CCUS** will be the main abatement lever for residual process emissions, reaching around ~62 Mt CO₂/year captured and contributing approximately ~43% of total CO₂ reductions, supported by fully deployed CO₂ transport and storage infrastructure. **Recarbonation and mineralisation** processes will be widely applied across cement and concrete products, delivering up to ~8% additional CO₂ uptake across the value chain. Overall, the sector will operate as a fully decarbonised industrial system with mature circularity, process optimisation and carbon management solutions integrated at scale.

PULP & PAPER

By 2050, the European pulp and paper sector is expected to achieve **climate neutrality** through the full deployment of electrification, renewable and low-carbon energy carriers, circular feedstocks, process optimisation and carbon management solutions. Fossil fuels will be fully replaced, with 100% integration of low-carbon energy carriers across production sites, enabling fully decarbonised heat and steam supply.

Direct electrification is expected to become the dominant decarbonisation route for most pulp and paper production processes, while alternative low-carbon fuels may play a complementary role in selected high-temperature applications where electrification is less technically feasible.

Process innovations such as **paper making without water evaporation** will reach commercial maturity, with >10 commercial-scale plants deployed, eliminating energy-intensive drying in selected applications. **Modular electrification and process optimisation** solutions will be widely integrated, with market penetration ranging from 10–70% depending on the specific process and site characteristics, reflecting the modular and flexible nature of these technologies and their varying applicability across mill configurations. **Mild and efficient pulping** technologies will reach around 50% market adoption, significantly reducing energy and chemical intensity across the sector.

Onsite renewable energy systems will be fully embedded in mill operations, supporting high levels of energy self-sufficiency, and **Bio-CCUS** will be deployed for residual emissions, with targeted integration in industrial clusters. In parallel, bio-based **product diversification** will become a structural pillar of the sector, contributing substantially to value creation and supporting a fully developed bioeconomy, with a significant increase in sectoral added value (up to +50% contribution).

CHEMICAL

By 2050, the European chemical sector is expected to achieve **climate neutrality** through the large-scale deployment of electrification, circular carbon feedstocks (waste, captured CO₂, biomass), renewable and low-carbon hydrogen, process optimisation and carbon capture and storage, subject to enabling conditions such as affordable renewable energy, infrastructure, and supportive policy and market frameworks.

Electrification will be widely deployed where technically and economically feasible, including indirect and direct processes (e.g., plasma, electrochemical processes) combines with efficient energy storage. **Alternative heat** and steam solutions such as **SMR** may contribute where relevant. Renewable / low carbon **hydrogen** will be used as feedstock and as an energy carrier where relevant, with deployment dependent on infrastructure and cost conditions. **Circular carbon** will be a key pillar, with widespread use of biomass, waste-derived feedstocks supported by chemical recycling, and captured CO₂, all dependent on feedstock and energy availability, cost competitiveness and regulatory conditions. **Process optimisation** and integration will improve overall efficiency, while carbon capture and storage will address residual emissions. **Deployment** will be linked to infrastructure availability, cost competitiveness.

ALUMINIUM

By 2050, the European aluminium sector is expected to achieve deep decarbonisation, reducing **greenhouse gas emissions** by more than 90% compared to 2021 levels.

Thermal processes are expected to be **electrified** by around 90% across the value chain where technically feasible, with hybrid solutions and low-carbon **hydrogen** used in the remaining hardest-to-abate high-temperature applications. In recycling and downstream operations, hydrogen combustion systems will be fully mature and integrated into low-carbon hydrogen supply chains, reaching approximately 30–50% penetration in technically suitable processes and regions with abundant and cost-competitive hydrogen availability.

Primary aluminium production will be transformed through the near-universal deployment of **near-zero-emission electrolysis** technologies, including inert anodes, with more than 90% adoption across the sector, effectively eliminating most process-related emissions.

Circularity will become a structural pillar of the sector through fully mature, high-efficiency scrap sorting and pre-treatment systems, enabling high-purity secondary aluminium to become standard

practice across recycling and downstream operations and significantly strengthening European resource autonomy.

Flexible electricity systems, digital controls and integrated storage solutions will become standard practice across aluminium production sites, enabling full alignment with renewable electricity supply and highly optimised industrial operations.

Waste heat recovery and energy efficiency measures will be widely integrated across the sector, with fully optimised waste heat recovery systems connected to electrified processes and digital energy management solutions, enabling deployment across approximately 70–90% of plants sector-wide.

Carbon capture and storage (CCS) will remain limited to niche applications for unavoidable residual emissions in hard-to-abate segments, complementing the primary decarbonisation pathways based on electrification, hydrogen and breakthrough electrolysis technologies.

3. Conclusions and next steps

This Thematic Vision outlines the **long-term pathway for energy intensive industries to achieve climate neutrality** by 2050 through the large-scale deployment of breakthrough technologies, system integration and circular economy principles. It provides a common strategic framework for aligning innovation, demonstration and deployment and policy priorities across SET Plan Countries, industry and research stakeholders, in line with the SET Plan objectives.

The Vision confirms that delivering economical industrial decarbonisation will require the **coordinated deployment of multiple technologies**, including electrification, hydrogen and alternative energy carriers, circular carbon and material flows, digitalisation, and carbon capture, utilisation and storage. In addition, system-level integration through industrial symbiosis, flexible energy systems and cross-sector coupling will be essential to enable cost-effective and resilient decarbonisation pathways.

In line with the SET Plan IWG-Industry Mandate, the next step will be the development of the **Strategic Research and Innovation Agenda** (SRIA) and the corresponding implementation framework for the sector. This process will be led by the technical sub-group of the IWG in close coordination with relevant stakeholder organisations, including industry associations, research actors and other relevant initiatives, such as the EU partnerships (e.g. CET, Process4planet and Clean Steel partnerships).

The SRIA development process will translate this Vision into actionable priorities, defining detailed research, innovation and deployment needs, as well as investment requirements along the full value chain.

Strong **synergies** are expected **with other SET Plan Implementation Working Groups**, reflecting the systemic nature of industrial transformation. Key areas of interaction include the IWG on Energy Systems, particularly on electrification, grids, flexibility and sector integration; the IWG on Hydrogen, regarding hydrogen supply, infrastructure and industrial applications; and the IWG on CCS/CCU, concerning CO₂ transport, storage and utilisation infrastructure and the IWG on Nuclear Safety, specifically in relation to safety aspects of Small Modular Reactors and their interfaces with energy system integration where relevant. Cross-cutting activities related to circularity, market access, digitalisation, and societal aspects – including skills development – will also be reinforced following the SET Plan Task Forces' recommendations.

Finally, the IWG will continue to **monitor progress** towards the Vision objectives through the SET Plan governance framework, ensuring regular updates of priorities in line with technological developments, market evolution and policy needs. Through coordinated action across SET Plan Countries, the European Commission, industry and research actors, the IWG aims to **support the deployment** of a competitive, resilient and climate-neutral European industrial base by 2050.

References

1 [2040 climate target - Climate Action - European Commission](#)

2 The analysis presented in this document builds on the following sectoral roadmaps and strategic documents developed by European industry associations:

- CEFIC. *Transition Pathway for the Chemical Industry*. [Cefic Transition Pathway](#)
- Cement Europe. *Cementing the European Green Deal: Reaching Climate Neutrality Along the Cement and Concrete Value Chain by 2050*. [From Ambition to Deployment - our 2050 Roadmap](#)
- Ceperi. *2050 Roadmap to a Low-Carbon Bioeconomy*. [Cepi 2050 Roadmap](#)
- ETN: [ETN Global R&D Recommendation Report](#)
- EUROFER. *Low-Carbon Roadmap: Pathways to a CO₂-Neutral European Steel Industry*. [EUROFER Roadmap](#)
- European Aluminium. *Net Zero by 2050*. [European Aluminium Net Zero by 2050](#)

3 Unless otherwise stated, all percentage improvements and emissions reduction estimates presented for the cement sector are assessed relative to the current average performance of the EU cement sector, using the 2021 technology baseline applied in the Cement Europe Net Zero Roadmap scenarios.

4 Sustainability criteria for biomass to be used as feedstock will be included in the section dedicated to biomass as feedstock.