TRANSITIONING TOWARDS AN EFFICIENT, CARBON-NEUTRAL CIRCULAR EUROPEAN INDUSTRY

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D3.7 – Industrial competitiveness and the EU twin transition

WP3 – Characterising circularity and decarbonisation opportunities – generating model inputs

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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

This deliverable is intended for the broader stakeholder community of TRANSIENCE, including policymakers, industry actors, and initiatives focused on industrial transformation and the circular economy. It provides an overview of planned analyses related to industrial competitiveness, with a focus on energy-intensive industries such as steel, cement, and chemicals, as well as clean energy technologies. The deliverable outlines upcoming insights into the challenges and opportunities for decarbonisation and circularity performance in these sectors, and highlights key areas of innovation, investment, and policy relevance.

3. Short summary of results (<250 words)

This deliverable examines the competitiveness and decarbonisation prospects of key EU industrial sectors: iron and steel, cement, chemicals, and clean technologies. It explores how these sectors can transition towards climate neutrality while sustaining their global market positions amid evolving regulatory frameworks such as the EU Emissions Trading System (ETS) and the Carbon Border Adjustment Mechanism (CBAM).

The analysis integrates sector-specific performance indicators, cost structures (CAPEX and OPEX), and enabling conditions, and highlights challenges such as high capital costs, raw material dependencies, and energy price volatility. In iron and steel, adoption of hydrogen-based reduction and electric arc furnaces is essential but capital-intensive. Cement faces considerable barriers due to process emissions, necessitating innovation in alternative materials and carbon capture. The chemicals sector's diverse pathways emphasise electrification and green hydrogen, while clean technologies are critical enablers but require secure supply chains and scale-up.

Cross-sectoral findings underscore the importance of coherent policies that support innovation, raw material access, and workforce development, while addressing risks of industrial relocation. The report advocates a balanced EU policy approach to maintain competitiveness and meet climate goals through investment in circularity, digitalisation, and skills.

Ultimately, the report provides actionable insights for policymakers to guide the EU's industrial transformation towards sustainability, resilience, and global leadership in the low-carbon economy.

4. Evidence of accomplishment

This report.

Preface

The need to approach climate action, resource efficiency, and circularity performance as integrated, economy-wide, cross-cutting issues is growingly gaining attention in the policy world, stimulating the development of new industrial policies in Europe and worldwide. Currently, however, there is little progress in conceptualising the circular economy and understanding its interactions with climate action. State-of-the-art modelling capacity to capture the interplay of the two agendas and their implications for energy-intensive sectors as well as to represent the European industry's transformation in line with the region's vision for climate neutrality is not yet fully developed. TRANSIENCE will undertake a comprehensive characterisation and assessment of circularity principles and measures vis-à-vis decarbonisation, by looking at the twin transition of European industries through the lenses of global competitiveness, innovation, and holistic sustainability. It will then produce MIC3, a consistent, fully open-source model ecosystem to assess industrial circularity, decarbonisation, and sustainability. A series of interoperable modules on the socioeconomic, service and product, material, industrial, energy-system, and environmental perspectives of the transformation of European industry will be developed and integrated, building on and opening the code of leading modelling tools. MIC3 will finally be used in extensive scenario modelling to produce diverse pathways toward a material-efficient, circular, climate-neutral, sustainable European industry. Transparency, openness, and knowledge sharing will be promoted, and technical capacities will be developed in four industrial agglomerations in the EU, moving beyond stakeholder consultation, onto model co-development, continuous validation of assumptions, co-creation of scenario modelling, evaluation of the desirability and usability of the developed model and insights, and eventually co-production of science and action.

ICCS – Institute of Communication and Computer Systems	EL
CEPS – Centre for European Policy Studies	BE
E3M – E3-Modelling AE	EL
Fraunhofer – Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.	DE
HOL – HOLISTIC IKE	EL
PIK – Potsdam Institut für Klimafolgenforschung e.V.	DE
PNTEC – Park Naukowo-Technologiczny Euro-Centrum Spolka Z Ograniczona Odpowiedzialnoscia	PL
TECNALIA – Fundación Tecnalia Research & Innovation	ES
UU – Universiteit Utrecht	NL
WI – Wuppertal Institut für Klima, Umwelt, Energie gGmbH	DE
PSI – Paul Scherrer Institut	CH
UCL – University College London	UK

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Executive Summary

This deliverable presents a comprehensive analysis of the competitiveness and decarbonisation pathways of key European Union (EU) industrial sectors—including iron and steel, cement, chemicals, and clean technologies—under the evolving framework of climate policies and global market pressures. It aims to elucidate the structural, economic, and technological factors shaping the transition toward a climate-neutral industrial base while maintaining EU competitiveness in the face of international challenges such as carbon leakage and raw material dependencies.

The analytical framework integrates performance indicators, enabling conditions, cost structures, and policy instruments, providing a multi-dimensional perspective on sectoral dynamics. The report assesses capital expenditure (CAPEX) and operational expenditure (OPEX) patterns alongside policy frameworks, including the EU Emissions Trading System (ETS), Carbon Border Adjustment Mechanism (CBAM), and Critical Raw Materials Act. This integrated approach highlights interdependencies between economic competitiveness, environmental sustainability, and policy effectiveness.

In the iron and steel sector, the shift to low-carbon technologies such as hydrogen-based direct reduction and electric arc furnaces is confronted by high capital costs and raw material constraints. Cement production faces significant decarbonisation challenges given its energy intensity and process emissions; innovation in alternative clinker formulations and carbon capture utilisation and storage (CCUS) are critical. The chemicals sector exhibits diverse pathways depending on feedstock sources and end-use applications, with electrification and green hydrogen playing pivotal roles. Clean technology industries, encompassing electrolysers, batteries, and renewable energy components, are essential for enabling decarbonisation but face challenges related to supply chain security and scaling.

Cross-sectoral analysis reveals persistent challenges linked to raw material supply, energy prices, and international trade dynamics. The report emphasises the need for coherent EU policies that foster innovation, ensure access to critical materials, and mitigate risks of industrial relocation. Investment in circularity, digitalisation, and workforce skills are underscored as key enabling conditions.

The deliverable concludes that a successful industrial transition requires coordinated action across policy domains, industry stakeholders, and research communities. The EU's regulatory framework must balance ambition with pragmatism, ensuring that competitiveness is preserved while achieving climate targets. This comprehensive assessment provides policymakers with actionable insights to support resilient and sustainable industrial transformation in the coming decades.

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1 Introduction

This document, "D3.7 – Industrial Competitiveness in the EU Twin Transition", is produced as part of the TRANSIENCE project, within Task 3.5: Competitiveness, Socioeconomic Implications, and Energy and Material Autonomy. It explores how key industrial sectors and clean technology value chains are positioned to respond to the demands of the green and digital transitions. The report contributes to assessing the enabling conditions, structural shifts, and policy frameworks that will shape Europe's industrial competitiveness in the context of climate neutrality and strategic autonomy goals.

1.1 Purpose and scope

This document explores the evolving landscape of industrial competitiveness in the context of the EU's twin transition, encompassing both green and digital transformations. It examines how Europe's industrial base, particularly in energy-intensive sectors and clean technology value chains, is adapting to the challenges and opportunities posed by decarbonisation and digitalisation.

The scope includes detailed assessment of key industrial sectors such as steel, cement, and chemicals, alongside clean energy technologies including solar, wind, batteries, and hydrogen. It also addresses cross-cutting issues such as circular economy strategies, infrastructure needs, and the policy environment. The analysis is framed by a structured approach to assessing industrial competitiveness, considering factors such as cost structures (CAPEX/OPEX), market positioning, innovation capacity, value chain integration, trade exposure, and regulatory conditions. This comprehensive framework aims to deepen understanding of the structural shifts and enabling conditions that will shape the EU's capacity to remain competitive while achieving its climate and sustainability ambitions.

1.2 Structure of the document

The document is organised as follows:

- Section 1 introduces this report, outlining its purpose, scope, and structure.
- Section 2 provides an overview of the role of industry in economic development and its central position in the green and digital twin transition. It highlights the challenges and opportunities facing energy-intensive industries and the clean-tech sector in the context of decarbonisation, circularity, and global industrial competitiveness.
- Section 3 presents the proposed framework for assessing industrial. It introduces two central pillars, performance indicators and enabling conditions, through which the competitiveness of energy-intensive and clean-tech sectors can be systematically evaluated, offering a structured lens to interpret policy implications, cost structures, and the risk of industrial relocation.
- Section 4, 5, and 6 examine individual Energy Intensive Industries (EIIs), Iron and Steel (section 4), Cement (section 5), and Chemicals (section6). Each section provides an in-depth overview of sector structure, the EU's competitive position, key decarbonisation challenges and opportunities, and relevant policy frameworks.

- Section 7 focuses on key clean energy technologies, such as solar PV, wind turbines, batteries, and hydrogen, highlighting their critical role in enabling industrial decarbonisation, and assessing the EU's position in their value chains, emerging challenges, and the policies shaping their development and deployment.
- Section 8 discusses the integration of circular economy strategies into macroeconomic and energy system models, highlighting their importance in decoupling economic growth from resource use and complementing earlier analyses on industry and clean technologies.
- Section 9 offers concluding remarks synthesising the main insights of the document.

2 Industry and the EU twin transition

Industry refers to the sector of the economy involved in the production of goods and related services through the processing of raw materials, manufacturing of goods, and construction of infrastructure. It encompasses a broad range of activities and is a fundamental component of economic development, employment, and trade, and plays a crucial role in shaping global supply chains and technological innovation.

The global industrial sector has been growing with an average annual rate of 3% in the period 2000-2023, driven by GDP growth, rapid industrialisation in emerging economies and increased global demand for industrial goods[1]. The average growth rate in the same period in the EU was only 1%[1], due to the higher economic maturity and slower GDP growth, shift towards service-oriented economy, higher operational costs and stringent regulations. From the beginning of the 21st century, the industrial sector represents 26%-28% of the global GDP[2] and employs 20%-24% of the global labour force[3]. Within the EU, the industrial sector in 2024 contributed to 22.2% of the GDP and directly employed approximately 44 million people, which represents about 22% of the EU workforce[4].

In addition to its economic significance, industry has a considerable impact on energy consumption and GHG emissions. Worldwide, in 2022 the industrial sector accounted for 37% of global energy use, equivalent to approximately 166EJ, up from 34% in 2002[5]. This increase has been primarily driven by the production rise of Energy-Intensive Industries (EIIs), such as iron & steel, cement, and chemicals. In 2021, industrial emissions accounted for 21% of global CO_2 emissions, and in 2022 the industrial sector was directly responsible for 25% of global energy system CO_2 emissions[6]. The industrial sector in the EU is responsible for about 25% (2022)[7] of the EU's final energy demand and has a share of 20% (2022) in EU's total emissions, making it a key sector in the transition to a decarbonised economy[8].

The twin transition refers to the simultaneous shift toward a green and digital economy. It is a key strategic concept in the EU's industrial and innovation policies, recognising that the green transition toward climate neutrality and sustainability, and the digital transition toward data-driven, automated, and smart systems, are interconnected and mutually reinforcing. At the same time, potential trade-offs should be acknowledged: while digitisation can support environmental goals, it may also lead to increased electricity demand from data centers and digital infrastructure,

[1] https://data.worldbank.org/indicator/NV.IND.TOTL.KD.ZG?end=2023&start=1961&view=chart&year=1960
[2] https://data.worldbank.org/indicator/NV.IND.TOTL.ZS?end=2023&start=1960&view=chart&year=2020
[3] https://data.worldbank.org/indicator/SL.IND.EMPL.ZS?end=2023&name_desc=false&start=1991&view=chart
[4] https://ec.europa.eu/eurostat/databrowser/view/nama_10_a10/default/table?lang=en&category=na10.nama10.nama_10_ma
[5] https://www.iea.org/energy-system/industry
[6] https://www.iea.org/energy-system/industry#tracking
[7] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_industry_-_detailed_statistics#:~:text=In%20the%20European%20Union%20(EU,and%20households%20(26.9%20%25
[8] https://ourworldindata.org/grapher/co-emissions-by-sector?focus=Industry~Transport~Manufacturing+and+construction~Electricity+and+heat~Buildings~Land-use+change+and+forestry~Aviation+and+shipping~Other+fuel+combustion~Fugitive+emissions

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which could make aspects of the green transition more challenging.

Given the substantial energy requirements of key industries such as steel, cement, and chemicals, where dominant energy carriers are still fossil fuels, mostly gas, coal, and oil, the challenge lies in transforming these industries into low-carbon, sustainable systems, while maintaining their competitiveness in the global market. The industrial sector is critical for the achievement of European climate goals, with the EU Green Deal and the recent Clean Industry Deal aiming to achieve a zero-carbon European industry by 2050 through the rapid uptake of clean energy forms and Carbon Capture and Storage (CCS), while ensuring affordability, cost competitiveness in international markets, sustainability, creation of high-quality jobs and security of supply.

As the European Commission (EC) acknowledges, the EU industry is undergoing a deep transformation, e.g., new technologies, need for greater resource efficiency, new business models, greater consumer demand for manufacturing activities being bundled with services. EC plans to revive new key industry sectors, e.g., construction, steel, paper, green technologies and renewable energies, manufacturing and maritime shipping (EC Juncker Plan, autumn 2017). The Europeans, at EU and national level, still have the ambition of EU industries playing an important role in international markets in the future.

The Clean Industry Deal is designed to support the decarbonisation of energy-intensive sectors, by promoting clean technologies (including CCUS), circular economy practices, and enhanced energy efficiency, to ensure that industries can achieve substantial emission reductions in line with the EU's climate neutrality goal by 2050 and its interim climate targets for 2030 and 2040. A key objective is to maintain and enhance the EU's industrial competitiveness on the global stage. The Deal supports investments in innovative processes (e.g., green hydrogen, electrification, CCS) to modernise plants and supply chains, increase productivity, and reduce operational costs over the long term. By fostering domestic production of critical clean technologies, the Clean Industry Deal aims to reduce dependency on non-EU suppliers for components and raw materials related to the climate transition. This contributes to economic resilience by mitigating vulnerabilities from global supply-chain disruptions. The EU's 'Net-Zero Industry Act' supports these goals and objectives by promoting the development and scaling of clean technologies, reducing the EU's reliance on imported fossil fuels, and ensuring that European industry remains globally competitive. However, the EU should ensure that this transition is not only environmentally sustainable but also economically viable with the European industry enhancing its global competitiveness. Achieving this balance requires the EU to align its ambitious climate goals with the preservation and strengthening of its industrial competitiveness. This is a particularly challenging task in the context of global industrial competition, trade dynamics, fluctuating energy prices, labour market transformations, and the need for substantial investments in new cleaner technologies.

The twin transition, green and digital, demands an urgent rethinking of Europe's industrial base. At its core lie two deeply interconnected sectors: Energy-Intensive Industries (EIIs) and the Clean-Tech sector.

Energy intensive industries are defined by their high energy and carbon intensity and have a significant role in value chains of most industrial products. EIIs, such as steel, cement, and chemicals are essential to the EU economy and the backbone of strategic value chains like car manufacturing. Historically these industries have driven large-scale economic progress (U.S.

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Department of Commerce, Economics and Statistics Administration, 1995), particularly in industrialised countries. The production and use of materials such as cement for infrastructure, steel for manufacturing and chemicals for a multitude of applications, have been key to societal and economic development. However, these industries, are among the most energy-intensive and carbon emitting sectors (IEA, 2024), raising concerns over their environmental impact and their role in climate change. As a result, the global drive towards sustainability and decarbonisation is placing pressure on these sectors to adopt greener practices, low- and zero-carbon technologies, circular economy practices, innovate in production processes and contribute to the achievement of global climate goals. In Europe these industrial sectors face enormous pressure from high energy costs, carbon pricing (as these industries participate in the EU ETS), global competition, and a complex regulatory landscape. Clean energy technologies, including electrification, green hydrogen, carbon capture, circular economy and energy efficiency solutions, are critical for the EU industry transformation. Without urgent support to deploy these technologies at scale, the competitiveness and future of EIIs are at risk.

The clean-tech sector is not just a tool for decarbonisation; it is the foundation of Europe's future industrial competitiveness. Technologies like wind turbines, solar panels, batteries, electrolysers, heat pumps, and digital energy management systems are key enablers of circularity, emissions reduction, and climate resilience. Their development and domestic production are essential to reduce dependencies on imported goods (as the EU currently imports vast quantities of solar PV and batteries from China), secure strategic autonomy, and create quality jobs[9].

These two sectors form a feedback loop: EIIs need clean-tech solutions to decarbonise, while the clean-tech industry needs a thriving industrial ecosystem to scale, deploy, and commercialise its innovations. In addition, some product of EIIs feature in the supply chain of green technologies, e.g., steel is required for wind turbines and EVs., Supporting both is not optional, it is indispensable for reaching climate neutrality, maintaining technological sovereignty, and ensuring the EU remains a global solutions provider.

In this context, clean energy technologies are not just climate tools, they should be seen as industrial policy instruments, geopolitical assets, and drivers of resilience and renewal.

[9] https://www.agora-energiewende.org/publications/ensuring-resilience-in-europes-energy-transition

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3 Framework for assessing the industrial competitiveness of EU

This section outlines a framework for assessing industrial competitiveness, with a particular focus on sectors at the core of the EU twin transition, energy-intensive and clean-tech industries. The framework combines two sets of indicators: performance indicators that track global positioning through metrics like trade balance, market share, investment and R&D (patents); and enabling conditions (indicators linked with production costs) that shape long-term competitiveness, including resource access and efficiency, workforce skills, and the regulatory environment.

Together, these indicators also help assess the exposure of industries to relocation risks, especially for industries facing high energy and carbon costs, regulatory complexity, and/or increasing global competition. Understanding these dynamics is critical to support strategic sectors, retain industrial capacity in Europe, and strengthen the foundations of a sustainable and competitive industry and economy.

3.1 Performance Indicators

Performance indicators capture the global positioning of industrial sectors and provide a quantitative basis for assessing their competitiveness. These metrics help track market dynamics, production capabilities, investment attractiveness, and overall economic performance.

The following indicators are particularly relevant:

- Production Volume: Measures the scale of industrial output in physical or monetary terms. It provides a foundation for understanding the size and strength of industrial activity.
- Industrial Production Growth Rate: Tracks changes in production over time, indicating whether a sector is expanding, contracting, or undergoing structural shifts.
- Global Production Share: Represents a region's contribution to global production. A higher share signals competitive manufacturing capacity and industrial leadership.
- Global Demand Share: Reflects the region's share of total global consumption of a given product or technology. A high demand share indicates that a significant portion of global needs originates from the region, underscoring the importance of maintaining or scaling up domestic production to meet internal demand, ensure supply security, and reduce dependence on imports.
- Export Market Share: Represents the proportion of global exports supplied by a region's industries. A higher export market share indicates that the region is effectively competing in international markets, reflecting both the quality and cost-competitiveness of its products. It also indicates the region's capacity to meet global demand, positioning it as a key player in international trade.
- Trade Balance (Exports – Imports): Highlights the difference between the value of exports and imports. A positive trade balance points to export strength (and thus increasing competitiveness), while a deficit may signal reliance on foreign production.

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Together, these indicators provide valuable insight into industrial performance and inform strategies to enhance resilience, competitiveness, and leadership in strategic sectors.

3.2 Enabling conditions/Drivers of competitiveness/Cost structure

The competitiveness of energy-intensive industries and clean technologies is closely tied to their underlying cost structure, which is shaped by the price and availability of energy, raw materials, labour, and capital investments. These industries often face high fixed costs and significant capital expenditure requirements, related to the installation of specific high-temperature industrial processes, their modernisation with more efficient industrial plants and their decarbonisation requiring uptake of capital-intensive technologies and processes. This makes them particularly vulnerable and highly sensitive to fluctuations in energy prices, carbon costs, and supply chain disruptions. To remain competitive in a rapidly evolving global market, especially during green and digital transitions, the energy-intensive industrial sectors require strong enabling conditions, including, access to affordable and reliable energy, efficient infrastructure, skilled labour, low-cost finance, and supportive regulatory frameworks. These factors not only reduce cost pressures but also enhance the ability of industries to invest in innovation, decarbonisation, and long-term resilience.

3.2.1 Capital Expenditure (CAPEX)

In energy-intensive industries (EIIs), capital expenditures represent a significant and often dominant component of the overall cost structure, particularly for new plants, technology upgrades, or decarbonisation efforts. These industries rely on large-scale, long-lived assets with high upfront investment costs, including kilns, blast furnaces, electrolysers, and chemical reactors. While operational costs, notably for energy, raw materials, and labour, remain substantial, the transition to low-carbon technologies shifts more weight toward capital-intensive solutions. For example, technologies like green hydrogen production or Carbon Capture and Storage (CCS) demand substantial additional capital outlays, often exceeding conventional alternatives in initial cost. As a result, access to affordable financing, long-term policy visibility, and de-risking mechanisms are essential to enabling investment without undermining their cost competitiveness.

3.2.2 Operational Expenditures (OPEX)

Operational expenditures remain a critical component of the cost structure in energy-intensive industries. These recurring costs, linked to the day-to-day functioning of production processes, include energy related costs, raw material inputs, maintenance, and labour. While they may not require the large upfront commitments of capital investments, operational costs have a direct and continuous impact on price margins, especially in sectors exposed to volatile commodity prices and international competition. Improving operational efficiency is therefore central not only to cost control but also to enabling a competitive and sustainable industrial transition.

Notably, most decarbonised technologies in the steel, cement, and chemicals sectors are expected to have higher operational costs than conventional processes in the short to medium term, due to increased energy use and alternative inputs. For technologies involving carbon capture and storage (CCS), these higher OPEX levels are likely to be permanent, given the ongoing energy and infrastructure demands. This underscores the need for efficiency improvements and supportive policy measures to sustain competitiveness during the transition.

3.2.2.1 Energy

Energy costs represent a significant share of operational expenses of energy-intensive industries, reflecting the inherently high energy demands of these industries. In 2023, energy expenses for EIIs in the EU accounted for approximately 8%-18% of total production costs[10]. Fossil fuels, especially coal and natural gas, remain dominant in the energy mix of these sectors, often amplifying costs especially in regions where carbon price mechanisms apply. Electricity in 2022 represented 33% of total energy consumption in the industrial sectors[11], however, it has a central role in decarbonisation pathways and alternative production technologies, such as the uptake of Electric Arc Furnace (EAF) in steelmaking, and emerging electrification and hydrogen-based processes in other sectors.

The EU faces some of the highest energy prices globally, driven by its strong reliance on energy imports, the impact of the Russia–Ukraine war, and carbon pricing under the EU Emissions Trading System (Figure 1). These pressures are compounded by electricity market rules, where gas often sets the electricity price, and national taxes and levies, placing EU energy-intensive industries at a significant cost disadvantage in terms of energy costs.

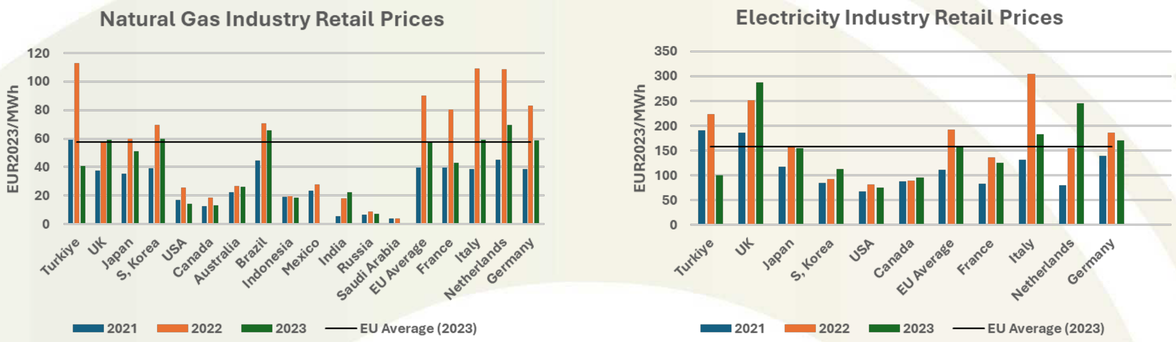

Figure 1. Natural gas and Electricity industry retail prices (excluding recoverable taxes and levies)[12]

Key non-EU competitors like China, the U.S., Brazil, India, and Türkiye have energy costs at least 20% lower and production costs at least 10% lower than the EU. For flat glass and pulp and paper, the gap may exceed 30%. Still, EU manufacturing is generally less energy-intensive than most international rivals[13].

3.2.2.2 Labour

A skilled and affordable labour force is key to the competitiveness of energy-intensive industries

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[10] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52025DC0072
[11] https://ebs.publicnow.com/view/A80CB56BDF430A2CF2B9FFB0119AA9FF32F08138?
[12] https://energy.ec.europa.eu/data-and-analysis/energy-prices-and-costs-europe/dashboard-energy-prices-eu-and-main-trading-partners-2024_en
[13] Study on energy prices and costs, 2024, https://op.europa.eu/en/publication-detail/-/publication/78756c15-f263-11ef-981b-01aa75ed71a1

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(EIIs) and clean tech sector. These sectors rely on technically trained workers to operate and maintain complex, often emerging, clean technologies. However, growing skills shortages combined with an ageing EU industrial workforce, high labour costs in some regions, and the need for large-scale reskilling and upskilling, driven by the green and digital transitions, pose challenges. Addressing these gaps is essential to ensure EIIs can decarbonise while remaining globally competitive.

Labour costs in the EU are generally higher than in many competing regions, such as parts of Asia, placing additional pressure on the cost structures of energy-intensive industries. For example, average hourly labour costs in the EU were around 34€ in 2024[14], compared to less than 10€ in countries like China or India. While the EU benefits from relatively high labour productivity, this advantage has narrowed over time and varies significantly across Member States and depends on the industrial sector. Maintaining competitiveness will depend not only on controlling labour costs but also on boosting productivity through automation, digitalisation, and continuous workforce upskilling, especially as EIIs transition to cleaner, more complex processes.

3.2.2.3 Raw Materials/Resources

Raw materials are a substantial component of the production costs in most energy-intensive industries such as steel, cement, and chemicals. These sectors depend on the continuous supply of specific inputs (raw materials), ranging from iron ore and coking coal (as a feedstock) to limestone, hydrocarbons, and various industrial minerals. The availability, price volatility, and supply chain reliability of these materials directly affect the operational efficiency and profitability of EU industries. As such, access to raw materials is not only an economic factor but a strategic one for EU EIIs, shaping decisions around plant location and long-term investment.

The European Union is highly dependent on imported raw materials to sustain its energy-intensive industries, including steel, cement, and chemicals[15]. Despite having some domestic extraction and processing capacity, the EU lacks sufficient reserves of many key inputs, such as iron ore, coking coal, and certain industrial minerals, making it vulnerable to global market fluctuations and geopolitical disruptions[16]. This import reliance is reflected in established trade flows, with Brazil, the United States, and Ukraine among the leading sources[17]. At the same time, the EU exports some raw materials and intermediate goods, particularly to China, the UK, and the U.S. To address these dependencies and bolster industrial resilience, the EU has launched initiatives like the Critical Raw Materials Act, aimed at diversifying supply chains, increasing recycling and domestic production, and strengthening strategic partnerships with key international players to ensure affordable and resilient supply of critical raw materials. However, securing long-term, affordable access to raw materials remains a critical challenge, especially as global demand for clean technologies increases pressure on supply. In line with the Clean Industrial Deal, the EU also plans to accelerate the implementation of the CRMA and has announced a forthcoming Circular

[14] https://ec.europa.eu/eurostat/databrowser/view/lc_lci_lev/default/table?lang=en
[15] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:Extra-EU_trade_in_raw_materials
[16] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en
[17] https://ecipe.org/publications/trade-diversification-the-role-of-mercosur/

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Economy Act to further strengthen resource efficiency and materials reuse.

3.3 Causes for loss of EU industrial competitiveness

The loss of EU industrial competitiveness is driven by several key factors. High energy costs in the EU, particularly in energy-intensive sectors like steel and cement, put EU industries at a disadvantage compared to competitors in regions with lower energy prices. High labour costs further strain competitiveness, especially as emerging markets offer cheaper alternatives. Additionally, limited access to finance hampers innovation and investment in modern technologies, while slow reskilling of the workforce slows adaptation to digital and green transitions.

Shifting global demand is another critical factor, with industries like steel and cement increasingly moving to developing countries where production costs are lower. Transportation costs, especially for bulky products like cement, further encourage this shift. The EU Emissions Trading System (ETS), while intended to reduce carbon emissions, may have a more significant impact on industry competitiveness in the future as carbon prices are expected to rise sharply, increasing operational costs. The EU ETS includes safeguards to protect industrial competitiveness, primarily through the free allocation of allowances. However, as these free allowances are set to decline and eventually phase out, this protection will diminish. To replace it, the EU is introducing the Carbon Border Adjustment Mechanism (CBAM). Yet, CBAM's effectiveness remains contested within the EU, with stakeholders questioning its practical impact, while several governments globally criticise it as a protectionist trade measure and an extraterritorial overreach.

Finally, rising protectionism and trade tariffs, especially following measures by the U.S., add additional pressure on the EU's industrial base. As trade barriers grow, the EU's access to global markets is increasingly restricted, further limiting its competitiveness. Addressing these challenges is critical for the EU to maintain its industrial strength and global market share.

The decision to relocate industrial activities has been driven by a combination of strategic, economic, regulatory, and environmental factors which are presented in (Table 1).

Table 1. Key drivers of industrial relocation

Key drivers	Description
Economic factors	- Cost reduction: Lower labour, energy, and operational costs in the destination country - Market Access: Proximity to growing markets to reduce transportation costs and tap into demand - Administrative capacity and quality of available transport infrastrucuture
Resource Availability	- Accessibility to raw materials, skilled labour, capital resources and/or infrastructure - Availability of renewable resources such as biomass for energy

	production and affordability of energy products
Technological factors	- Investments in new technologies or facilities to modernise production processes - High-skilled labour with the required technical skills
Environmental and energy considerations	- Access to cleaner energy sources or proximity to CO_2 storage facilities for emission management
Policy and regulatory environment	- Stringent environmental regulations in the original location can encourage relocation to regions with more lenient policies - Financial incentives, such as tax breaks or subsidies offered by destination regions

3.4 Potential impacts of loss of industrial competitiveness in the EU

The loss of industrial competitiveness in the EU, especially in energy-intensive industries and clean technologies, can have wide-reaching economic, environmental, and social consequences which can impact the success of the twin transition. A competitive industrial base is essential to support economic growth and innovation, maintain high-quality employment, and produce the materials and technologies required for climate neutrality. Loss of competitiveness, due to high capital, energy and operational expenditures, global market pressures, or lack of investments and skilled labour, will have impacts that ripple across the entire economy. It can weaken its innovation capacity, reduce productivity, and diminish the EU's role in global industrial value chains.

One of the most serious consequences of declining competitiveness is the risk of industrial relocation. Companies facing increasing costs and structural disadvantages in the EU may choose to shift their production to countries with lower operational costs or less stringent environmental and regulatory requirements.

Over the past several decades, industrial relocation (the process of shifting industrial activities or facilities from one geographical location to another) has been a central feature of global trade dynamics, with many energy-intensive industries shifting operations to regions with lower labour and energy costs. This movement has been largely driven by production cost differentials, access to raw materials and less stringent environmental regulations in non-EU countries. However, the evolving global landscape, especially with the pressing need for climate action, is influencing a shift in industrial dynamics. The twin transition, the simultaneous and interconnected processes of the green and digital transition, presents an opportunity to rethink these patterns of industrial relocation and explore how industries can adapt or reshore operations in response to evolving policy, market demands and technological advancements. In addition, the climate transition creates opportunities for the creation of new industries to manufacture clean energy and digital technologies, related products and infrastructure with the potential to generate new high-quality jobs and income for EU citizens.

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It is important to acknowledge the potential positive impacts of the relocation industries to non-EU regions, in example relocation of steel production to non-EU regions. Lower steel production costs in these regions could benefit EU downstream industries, such as car manufacturing. With access to cheaper imported steel, EU car manufacturers can reduce production costs, making their vehicles more competitive in the global market. This shift may, therefore, provide a cost advantage for sectors that rely on steel as an input for more complex products, supporting overall EU industrial competitiveness in certain areas.

3.4.1 Environmental impacts of relocation

The EU Green Deal is a central pillar of the EU's strategy for achieving climate neutrality by 2050, positioning the EU as a global leader in climate action. One of its core elements is the EU Emissions Trading System (EU ETS), a cap-and-trade mechanism that limits carbon emissions from sectors such as energy, industry, and aviation. Through the EU ETS, companies must buy allowances to emit CO_2, creating a financial incentive to reduce emissions and invest in clean energy and efficient technologies.

The EU's carbon policies are among the most stringent globally, creating strong incentives for industries to reduce emissions and adopt cleaner technologies. However, high carbon prices under the EU ETS increase energy costs, which in turn raise production costs for EU industries. This can increase the risk of industrial relocation to countries with limited or no environmental regulations. As a result, industrial products are often manufactured in regions with higher carbon intensity than the EU (e.g., producing 1 ton of steel in China or India results in significantly higher emissions compared to the EU). This phenomenon, known as carbon leakage, can ultimately lead to an increase in global emissions. This could undermine the EU's efforts to reduce global emissions while jeopardising its competitive edge in certain industries, especially those that are energy-intensive and face high carbon costs, such as cement, steel, and chemicals.

To address this, the EU has recently introduced measures like the Carbon Border Adjustment Mechanism (CBAM), which aims to level the playing field by imposing a carbon price on imports from countries with weaker climate policies. This ensures that European industries do not lose their international competitiveness due to high carbon pricing, and that global carbon reduction efforts are not compromised by the relocation of high-emission production outside the EU. While the goal is to prevent carbon leakage, it also encourages other regions to adopt more ambitious climate policies, thus fostering global climate cooperation.

3.5 Strategy and roadmap of the EU industrial sector

3.5.1 Investments, innovation, and digitalisation

Over the period 2025 to 2040, total investments needed to support the transformation of assets and processes of key energy-intensive industries (EIIs) are estimated at around EUR 500 billion (The future of European competitiveness, 2024[11]). Within this timeframe, approximately EUR 340 billion would be required for the four largest EIIs (chemicals, metals, non-metallic minerals, and pulp and paper) between 2031 and 2040, with around EUR 100 billion specifically allocated to the steel sector[18].

However, the deployment of low-carbon solutions faces several obstacles. High capital costs, low Technology Readiness Levels, the absence of viable business models, and limited infrastructure, such as hydrogen networks or carbon capture and storage (CCS) facilities, remain key barriers. Furthermore, in current market conditions, green products, including those made from recycled materials, rarely command price premiums sufficient to offset their elevated production costs, making early adoption economically challenging.

These challenges are compounded by the structural characteristics of energy-intensive industries, which typically operate with long investment cycles and capital assets that remain in place at least 30 to 40 years. Furthermore, these investments must take place at a time when global overcapacity and low utilisation rates[19,20] make any new capacity additions, whether green or conventional, especially difficult. This increases the risk of lock-in, particularly when retrofitting existing installations is either technically unfeasible or financially prohibitive. Without strong incentives or targeted support, firms may defer clean energy investments, resulting in missed opportunities for timely decarbonisation.

While the EU Emissions Trading System (ETS) generates significant revenues, its current allocation does not sufficiently support the industrial transition. Only one quarter of ETS revenues is channelled into the Innovation Fund, with two thirds directed to the Modernisation Fund, which primarily supports energy system upgrades in 13 low-income Member States. The remaining revenues are redistributed to national governments. Between 2013 and 2022, EU Member States reported allocating 76% of ETS revenues to climate-related spending, but over 55% of this was used for (renewable-based) electricity subsidies and buildings' retrofits and upgrades rather than supporting industrial decarbonisation.

In this context, funding levels for low-carbon industrial transformation remain inadequate. Instruments such as the Modernisation Fund do not directly support EIIs, and existing public financing mechanisms fail to de-risk early-stage investments or ensure the bankability of large-scale industrial transformation projects. Bridging this financing gap and ensuring a more effective use of ETS revenues will be essential to accelerate the deployment of low-carbon technologies in Europe's industrial base.

3.5.2 Business & regulatory environment and related international policies

3.5.2.1 European regulatory environment

The European regulatory environment for industrial sectors is shaped by a complex framework of

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[18] https://commission.europa.eu/document/download/ec1409c1-d4b4-4882-8bdd-3519f86bbb92_en?filename=The%20future%20of%20European%20competitiveness_%20In-depth%20analysis%20and%20recommendations_0.pdf
[19] https://www.steelorbis.com/steel-news/latest-news/oecd-overcapacity-problem-to-worsen-and-impact-markets-in-future-1308305.htm
[20] https://globalcement.com/news/item/16481-world-cement-association-warns-of-sector-overcapacity-and-emission-targets

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policies aimed at balancing economic competitiveness with environmental sustainability. This includes climate legislation such as the EU Emissions Trading System (ETS), energy efficiency directives, and product and waste regulations, alongside industrial policy initiatives like the Green Deal Industrial Plan and the Net Zero Industry Act, and recently the Clean Industrial Deal. Together, these policies set the direction for decarbonisation, innovation, and market integration, while increasingly influencing investment decisions, production standards, and cross-border trade within and beyond the EU.

Key EU policies which have an impact on the industrial sector and energy-intensive industries are shown in Table 2.

Table 2. Key EU policies with an impact on the industrial sector

Policy/Initiative	Purpose & Key Objectives	Target Industries	Comments
EU Emissions Trading System (EU ETS)	Market-based mechanism to reduce GHG emissions by setting a cap and allowing trading of allowances.	Power generation, steel, cement, chemicals, aviation, and other EIIs.	Currently in Phase 4 (2021–2030); ETS2 to cover buildings and road transport from 2027.
Carbon Border Adjustment Mechanism (CBAM)	Prevent carbon leakage by imposing a carbon price on imports of selected goods.	Cement, iron and steel, aluminium, fertilisers, electricity, hydrogen.	Transitional phase underway; will gradually align with EU ETS pricing.
Industrial Emissions Directive (IED) **&** *Best Available Techniques (BAT) Reference Documents (BREF)*	Regulates pollutant emissions from industrial installations to protect health and the environment.	Power plants, refineries, metals, cement, chemicals, pulp & paper, others.	IED 2.0 entered into force August 2024; updates BAT standards.
Net-Zero Industry Act (NZIA)	Strengthen EU production capacity for clean tech.	Solar, wind, batteries, heat pumps, electrolysers, CCUS.	40% of EU clean tech deployment needs to be produced domestically by 2030.
Green Deal Industrial Plan	Enhance net-zero industry competitiveness and scale up clean tech	Clean tech, EIIs, renewables.	Supports domestic manufacturing of strategic net-zero technologies.

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	production.		
Clean Industrial Deal	Reassert EU clean industrial leadership and competitiveness.	Clean tech, energy-intensive industries.	Accelerates CRMA implementation and announces a forthcoming Circular Economy Act.
Critical Raw Materials Act (CRMA)	Secure supply chains for critical materials.	Clean tech, aerospace, defence, digital sectors.	Sets benchmarks for domestic sourcing, processing, and recycling.
Circular Economy Action Plan (CEAP)	Promote sustainable production and consumption; reduce waste; support secondary materials markets.	Cement, steel, chemicals, construction, batteries, electronics.	Emphasis on material efficiency, industrial symbiosis, and sustainable product design in EIIs and clean tech sectors.
Energy Efficiency Directive (EED)	Set binding targets for energy efficiency.	Industry, buildings, transport.	32.5% efficiency target by 2030.
Renewable Energy Directive (RED)	Promote renewable energy use.	Power, heating, transport sectors.	42.5% binding RES target by 2030; 45% aspirational.
REPowerEU Plan	Diversify energy supply, accelerate clean energy deployment.	Hydrogen, renewables, infrastructure, EIIs.	Response to Russian invasion of Ukraine; supports energy transition investments.
Innovation Fund	Fund innovative low-carbon technologies through EU ETS revenues.	EIIs, renewables, CCS, storage.	Supports large and small-scale projects.
EU Chips Act	Strengthen semiconductor supply chain resilience and capacity.	Digital, automotive, defence, electronics.	Targets 20% global chip market share by 2030; links to industrial competitiveness.
Circular Economy	Enhance legal framework for	EIIs, clean tech,	Announced alongside Clean Industrial Deal;

Act	circularity in key value chains.	manufacturing.	details forthcoming.
Bioeconomy Strategy	Support sustainable use of biological resources.	Agriculture, forestry, food, chemicals.	Updated to support circular bio-based industries and climate neutrality.
Steel and Metals Plan	Address decarbonisation and competitiveness of the steel and metals sectors.	Steel, non-ferrous metals.	Expected to align with CBAM, ETS reforms, and green public procurement.
Chemical Industry Plan	Strengthen resilience and sustainability of EU chemical production.	Chemicals, petrochemicals.	To address high energy costs, competitiveness, and regulatory burden.
Automotive Industry Plan	Support transition to zero-emission mobility.	Automotive, batteries, EV supply chains.	To complement CO_2 standards, battery regulations, and Euro 7.
Industrial Decarbonisation Accelerator Act	Accelerate deployment of clean tech and infrastructure for hard-to-abate sectors.	EIIs, hydrogen, CCUS, clean fuels.	Still under discussion; may offer permitting and financing support.
Clean Industry State – Aid Framework	Enable flexible public support for green industry under EU rules.	Clean tech, manufacturing.	Updated in 2023 to match global subsidy competition (e.g., US IRA).
Affordable Energy Action Plan	Ensure stable and affordable energy for industry and households.	All energy users.	Under development; includes demand response, price stabilisation, and energy efficiency tools.
Clean Trade and Investment	Align trade and industrial strategy	EIIs, clean tech exporters/importers.	Promote clean supply chains and address

Partnerships	with climate goals.		trade tensions linked to decarbonisation measures.

3.5.2.2 International trade policies and industrial protectionism

Trade has long been an engine for growth, facilitating innovation, specialisation, enhanced productivity, and economic development across nations. Over the past two decades, global trade has expanded significantly as trade barriers have declined, evidenced by falling tariff rates and the rise of global value chains. This liberalisation of trade has enabled countries to integrate more deeply into the global economy, driving economic growth and fostering technological advancement. For instance, the EU has benefited from both increased exports and access to key raw materials and technologies through international trade agreements and reduced tariffs.

However, in recent years, a radical shift in this trend of globalisation is observed. International trade policies beyond the EU increasingly feature elements of industrial protectionism that affect European industrial competitiveness. Key examples include import tariffs, local content requirements, and subsidy schemes designed to favour domestic producers[21]. For instance, the U.S. Inflation Reduction Act offers generous subsidies to clean technology manufacturers on the condition that production occurs within North America, disadvantaging EU exporters.

Similarly, India and Indonesia have imposed export restrictions or high tariffs on key raw materials like nickel and bauxite, directly impacting EU industries dependent on these inputs. China's strategic control and export quotas on critical minerals such as rare earths also pose risks to European supply chains, i.e. for battery and EV manufacturing. These protectionist trends, especially tariffs, not only limit EU industrial access to foreign markets and resources but also increase the urgency for a coherent trade and industrial policy that defends European competitiveness while ensuring diversified and resilient supply chains. Several restrictions are based on temporary instruments increasing the uncertainty of planning long-term strategies.

[21] https://www.imf.org/en/Publications/WP/Issues/2023/12/23/The-Return-of-Industrial-Policy-in-Data-542828

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4 Iron and Steel industry

The iron and steel sector is an important pillar of Europe's industrial economy, supplying key value chains from construction to automotive. The EU27 steel industry has an annual output of roughly 150 million tons of steel (about 8% of global production) and a turnover around €120–130 billion, directly employing over 300,000 people[22].

However, the European steel sector is facing increasing challenges, especially due to the rising international competition and high cost of decarbonisation. China alone produces about half of the world's steel (1.9 billion tons globally in 2022), while the EU domestic production has declined by roughly one-third since the 2008 financial crisis. This contraction, alongside a 25% drop in steel sector employment over the past decade, reflects the increasing production costs that the EU steel manufacturers face (high energy costs, high labour costs, ETS carbon costs) and severe overcapacity particularly from China, but also reflects efficiency improvements and competitive pressure from low-cost, carbon-intensive overseas producers, of course, including China[23].

To illustrate the scale and urgency of the challenges currently affecting the European steel sector, EUROFER – the European Steel Association representing the EU's steel producers, together with industriAll European Trade Union, sent a joint letter in December 2024 to Ursula von der Leyen, President of the European Commission, and Executive Vice-President Stéphane Séjourné[24]. The letter described a critical situation marked by thousands of job losses and the suspension of billions of euros in planned investments in the steel sector. It denounced the severe impact of a renewed surge in low-cost steel imports, particularly from China, which alone is estimated to be exporting around 100 million tonnes at dumping prices. This trend is occurring within a context of record global overcapacity, in 2023 was estimated at 551 million tonnes according to OECD figures[25] n addition to China, regions and countries such as South Asia, the Middle East, India, and Japan are also redirecting excess production towards the EU, depressing prices and threatening the survival of the European steel industry. Moreover, the letter called for short-term emergency measures, stronger trade defence instruments, and the urgent organisation of a high-level European Steel Summit to develop a coordinated response and safeguard the sector's future competitiveness and green transition efforts[14].

Maintaining Europe's competitiveness in steel manufacturing during the twin transition is therefore a key policy concern and this document will provide an overview of the key elements for the EU competitiveness in this sector including in 4.1 market position, production and trade, 4.2 the main technological routes and decarbonisation option and in 4.3 the enablers for Steel competitiveness in EU.

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[22] EUROFER 2022, European Steel in Figures 2022, European Steel Association – Key statistics
[23] S&P Global Commodity Insights 2024, Commodities 2025, Dec 2024
[24] https://www.eurofer.eu/publications/position-papers/steel-crisis-urgent-meeting-and-eu-summit-needed-to-discuss-urgent-solutions
[25] Rimini, M., Corneille, A., Gu, D., & Yamin, M. (2025). Hydrogen in steel: Addressing emissions and dealing with overcapacity (OECD Science, Technology and Industry Policy Papers No. 1742). OECD Publishing

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4.1 Market position, production and trade

4.1.1 Global and EU steel production: main highlights

Steel Production, demand and utilisation rate: current status

According to the World Steel Association, global crude steel production reached 1,892 million tonnes in 2023. This reflects a relatively stable trend since 2020, with an average annual growth of the steel production rate of only 0.4%, following a more dynamic 3% annual growth observed between 2015 and 2020. In 2023, global per capita steel use in new products was estimated at 219 kilograms[26].

A comparison between 2023 and 2022 confirms the overall stability in global steel production, with total output increasing marginally from 1,890.2 to 1,892.2 million tons. China's production remained unchanged at 1,019.1 Mt, continuing to account for more than half of global output. India recorded the largest absolute increase among the top producers, growing from 125.4 to 140.8 Mt, thereby strengthening its position as the second-largest global steel producer. Among the other top ten countries, Russia and the United States experienced moderate growth, while Japan, Germany, and Brazil recorded small declines. Germany maintained its seventh position, but its output fell from 36.9 to 35.4 Mt. Italy's production also declined slightly, from 21.6 to 21.1 Mt. Across Europe, several countries showed signs of contraction. France experienced a drop of 2.1 Mt, while Poland, Belgium, and the Netherlands each reduced production by around 1 Mt or more. Conversely, Spain and Austria maintained relatively stable levels.

Germany ranked seventh globally, with 35.4 million tons of steel production, significantly behind the top six and representing the only EU country among the global top ten. Italy, which was previously among the top producers, ranked 11th in 2023, with 21.1 million tons, having been overtaken by Turkey, Brazil, and Iran, each producing more than 10 million tons more than Italy. Other European countries in the top 20 included Spain (17th, 11.4 Mt) and France (19th, 10.0 Mt). The share of production in the European countries is presented in Figure 2.

Overall, **steel production in the EU27 amounted to 126.3 million tons in 2023, representing approximately 6.7% of global output.**

A closer look at the **EU 27 trend shows that crude steel output in 2023 was some 19.5 % below its pre-COVID peak in 2019 and about 21.3 % lower than in 2010.** This underlines a significant decline in European steel production over the past decade, even before the COVID pandemia, and highlights the growing gap versus emerging producers. Figure 3 illustrates crude steel production for the EU 27, China and India from 2010 to 2023.

[26] World Steel in Figures, 2024

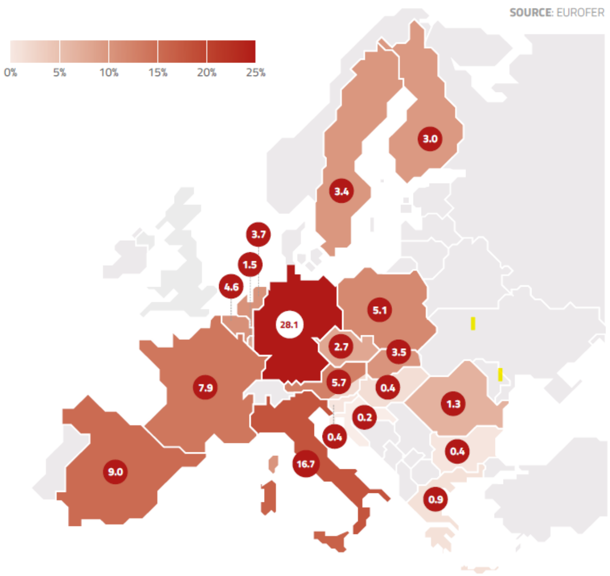

Figure 2. Share of crude steel production in EU countries. Source Eurofer European Steel in Figures, 2024

This chart makes clear how China's and India's rapid expansion has contrasted with Europe's gradual decline, reshaping the global steel landscape and confirms the relative decline of the European Union in the global steel landscape, both in terms of absolute volume and presence among the top producing countries

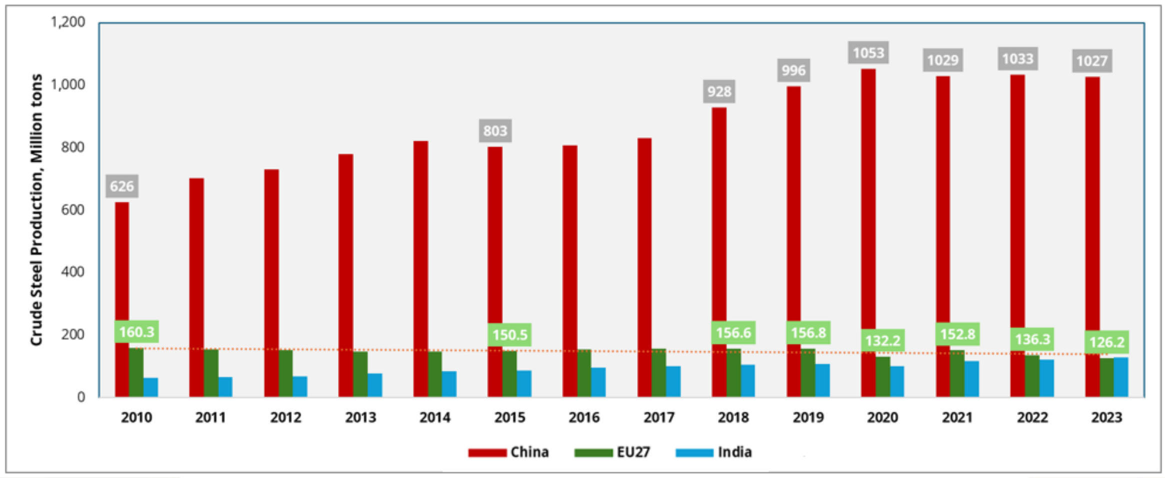

Figure 3. Crude steel production, 2010–2023: historical series for EU 27 (with UK production subtracted for 2010–2019 to ensure consistency), Own elaboration based on Eurofer publications *Steel in Figures* and World Steel Association *World Steel in Figures (2019-2024)*

Despite the decreasing importance of the sector in EU, production is still able to cover most of the EU's domestic demand of steel, around 90% according to Eurofer (139 million tons of real consumption) [Eurofer, 2023].

According to **the recent European Steel and Metals Action Plan published by the Commission on 19 March 2025**, ThyssenKrupp announced plans for 11,000 lay-offs in Germany in December 2024 while, in November 2024, ArcelorMittal has postponed its decarbonisation investments across Europe. Additionally, Liberty Ostrava announced bankruptcy in Czech Republic in June 2024

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[European Commission, 2025; An European Steel and Metal Action Plan[27]]. With current capacity utilisation in the steel sector hovering around 65%, the industry is operating well below levels needed for long-term economic viability. Given the capital-intensive nature of steel production, maintaining competitiveness under normal market conditions typically requires utilisation rates exceeding 85% [European Commission, 2025; An European Steel and Metal Action Plan].

The data highlights a structural shift in the global steel industry, with increasing contributions from emerging economies and a gradual decline in Europe's share in global production.

4.1.2 Employment, Gross Value Added and Capacity Utilisation

Beyond output volumes, employment and value-added indicators provide a broader view of the sector’s socio-economic contribution. The analysis of the data available in Eurofer statistics and elaborated in Figure 4, the post-crisis downturn in EU 27 steel output from 160 Mt in 2010 to 147 Mt by 2013–14 was accompanied by a steep fall in direct employment, from 366 thousand to 327 thousand, and a collapse in GVA, from €198 billion to €118 billion. As volumes recovered toward 157 million tons in 2018 and 2019, workforce numbers stabilised around 330 thousand even as GVA rebounded to €140–148 billion, indicating that value-added growth outpaced job creation. The 2020 pandemic shock again reduced production to 132 million tons with GVA held at €141 billion thanks most probably to temporary price spikes, while employment dipped only marginally to 327 thousand. As mentioned in the previous paragraph, between 2021 and 2023, the production of crude declined further to 126 Mt (21.3 % below 2010), and jobs fell to 303 thousand (17 % below 2010), but GVA climbed to a new high of €152 billion. This divergence between GVA, production and employment highlight the sector’s growing reliance on higher unit margins and efficiency gains. Despite a smaller workforce and lower volumes, the EU steel industry has managed to enhance value creation

[27] https://single-market-economy.ec.europa.eu/document/download/7807ca8b-10ce-4ee2-9c11-357afe163190_en?filename=Communication+-+Steel+and+Metals+Action+Plan.pdf

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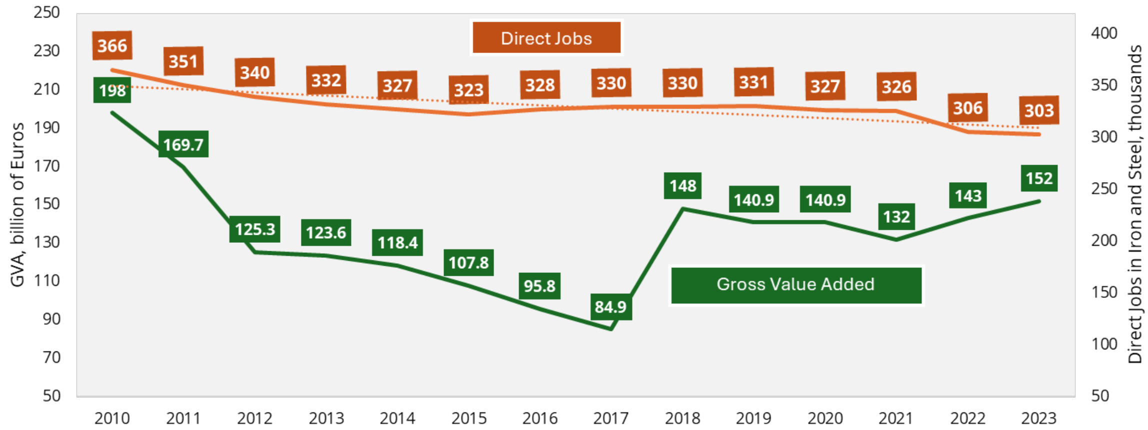

Figure 4. Direct jobs in steel production, 2010–2023: historical series for EU 27. Own elaboration based on Eurofer publications *Steel in Figures (2019-2024)*

4.1.3 Trade Flows, Tariffs and Global Competition

Europe is a steel trading country, traditionally exporting high-quality steel products (e.g. to the US, UK and Turkey) and importing lower-cost materials (including semi-finished and finished steel from China, Turkey, Russia, and others). However, in 2024, imports of flat steel products to the EU rose by 30% in the first four months, putting pressure on domestic producers[28,29]. Hence, the competitiveness of the European steel industry is currently under pressure from multiple, interrelated challenges. First, a surge of low-cost steel imports, especially from China, has flooded the EU market, driving down prices and threatening the viability of domestic producers. This trend is compounded by the upcoming expiration of EU safeguard measures, which risks exposing the sector to further import shocks[28]. At the same time, EU producers are facing restricted access to the US market due to tariffs, while simultaneously competing with Chinese exports redirected from the US. Moreover, Europe's ambitions to lead in green steel are undermined by delays in investment in low-carbon technologies and infrastructure, as companies hesitate in the face of regulatory and economic uncertainty and limited support for hydrogen and infrastructure development.

Possible Effects of US Trade War on EU Steel Export

The U.S. trade war, reignited in 2025 under President Trump, has imposed 25% tariffs on EU steel, severely impacting European exporters. The U.S., previously the second-largest market for EU steel, now poses significant challenges for European producers. Salzgitter AG, a major German steelmaker, anticipates a reduction of 2–3 million tons in EU steel exports, potentially doubling if tariffs persist.
This move echoes Trump's 2018 decision to impose a 25% tariff on steel and 10% on aluminium, initially citing national security concerns. At the time, the EU responded with retaliatory tariffs on

[28] https://www.eurofer.eu/statistics/trade-statistics/imports
[29] https://www.ft.com/content/eff50cd7-3cdf-4410-98ee-f13631226383

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€2.8 billion worth of U.S. goods, including symbolic products like bourbon and motorcycles. U.S. carmakers such as Ford and GM reported financial losses, while domestic steel producers raised prices without significantly increasing output.

The EU is actively negotiating with the U.S. to resolve these trade tensions but is also preparing countermeasures targeting up to €95 billion in U.S. goods, including cars and machinery [30].

With existing EU safeguard measures set to expire in 2026, there is an urgent need for strategic action to protect the European steel industry. The EU's commitment to a negotiated solution remains strong, but preparations for potential retaliatory measures underscore the seriousness of the situation.[31,32]

4.2 Steel Technological Routes, Energy Use and Emissions

The iron and steel industry is among the most energy- and emissions-intensive sectors in Europe, accounting for roughly 5% of the EU's total CO_2 emissions. This section provides an overview of the main production routes and their energy and carbon intensity, identifies key decarbonisation pathways, and highlights the strategic implications of resource dependency for EU competitiveness.

4.2.1 Technological Routes and decarbonisation options, energy and carbon intensities

Steel production can be classified into primary and secondary processes, depending on the raw material inputs needed and the process route and the final use. Primary steel is produced by converting iron ore into steel requiring carbon in form of coke that is obtained though coking coal, and injection of coal at high temperature heat to reduce iron ore. The traditional process is the integrated Blast Furnace–Basic Oxygen Furnace (BF–BOF) route; the integrated route includes sinter plants, coke ovens and the BF-BOF plant. Alternatives to the traditional route are Direct Reduced Iron–Electric Arc Furnace (DRI–EAF) and Smelting Reduction (SR) processes. The integrated BF–BOF cycle involves ore preparation through sintering or pelletising, forming a uniform feed reduced in a blast furnace primarily using coke and producing pig iron. In the BOF the pig iron, refined in a basic oxygen furnace.

According to IEA and World Steel Association[33], the global average energy intensities of the three main routes are:

1. **BF-BOF (based on coal): 21.4 – 22.7 GJ/t**
2. **DRI-EAF based on natural gas: 17.1 – 21.8 GJ/t**

[30] https://www.reuters.com/business/autos-transportation/eu-analysing-us-uk-trade-deal-impact-eu-global-trade-2025-05-12/.
[31] https://www.reuters.com/markets/commodities/eu-debates-support-europes-steel-industry-us-tariffs-loom-2025-03-04/
[32] Financial Times: available at https://www.ft.com/content/17a5f5f3-591a-475d-8f08-e112a12b66b7
[33] IEA (2020), Iron and Steel Technology Roadmap, IEA, Paris https://www.iea.org/reports/iron-and-steel-technology-roadmap

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3. **Scrap-based EAF: 2.1 – 5.2 GJ t**

The differences in the presented values depend on the choice of energy accounting boundary: the IEA reports energy intensities in terms of final energy, while World Steel Association uses primary energy terms for electricity consumption. Specifically, World Steel applies a conversion factor of 9.8 GJ of fuel per MWh of electricity, equivalent to a 37% conversion efficiency. As a result, processes that rely on electricity appear more energy intensive under the World Steel analytical boundary compared to the final energy-based boundary used by the IEA[21].

The IEA also provides energy intensities for innovative and commercial technology routes that, of course, are much more energy efficient compared to the conventional BF-BOF route. In particular, the commercial BF-BOF process requires approximately 19.7 GJ of energy per tonne of crude steel, emitting around 1.2 tonnes of direct CO_2 per tonne of steel produced, or 2.2 tonnes per tonne of steel when including indirect emissions[34].

An alternative primary steel route, the DRI–EAF process, reduces iron ore pellets or lump ores in dedicated reactors using mainly natural gas as reducing gases. The direct reduced iron (DRI) is then melted in an electric arc furnace EAF. The main difference between the direct reduction and the traditional BF-BOF route are: a) the type of iron used that in case of the DR-EAF route is limited to high quality DRI pellets while the BF-BOF has more flexibility and can use iron ore with impurities and also combined with pellets, fines, sinter and lump ore; b) the state of the reduced material: solid state in DRI furnace with addition of some scrap while liquid phase in BF; c) less flexibility in the kind of fuel used: BF-BOF can use only coke and coal while DR-EAF could use also coal to generate reducing syngas

The commercial natural gas-based DRI–EAF installation consumes roughly 13.1 GJ per ton, with direct CO_2 emissions around 1.0 tonne per tonne, rising to 1.4 tonnes per ton when indirect emissions from electricity generation are included. In the hydrogen-based DRI–EAF configuration, a key decarbonisation option, the process requires approximately 16.6 GJ per ton of crude steel (reflecting high electricity input for hydrogen electrolysis) but can achieve nearly zero direct emissions if renewable electricity is used for the production of green hydrogen. Another promising primary steelmaking route is the smelting reduction (SR), with technologies like Corex® and Finex® that integrate reduction and melting using non-coking coal and oxygen injection in a single reactor. The SR route with carbon capture consumes about 15.6 GJ per tonne and provides substantial emissions reduction potential compared to conventional BF–BOF processes, especially when integrated with CCUS technologies [IEA, 2020, Iron and Steel Roadmap; IEA, 2020, The Future of Hydrogen].

The secondary steel production uses recycled scrap steel as its main input. The scrap-based EAF route directly melts ferrous recycled scrap in an electric arc furnace. This route is largely electrified; however, a small amount of natural gas and coal are still used in electric arc furnaces to provide supplemental heat and support slag foaming. A smaller share of direct CO_2 emissions also results from the consumption of graphite electrodes, bringing total emissions to around 0.06 to 0.1 tCO_2

[34] https://www.iea.org/reports/the-future-of-hydrogen

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per tonne of steel [European Commission: Joint Research Centre and Somers, 2022. J., *Technologies to decarbonise the EU steel industry*, Publications Office of the European Union[35]].

The electricity demand is estimated at around 2.1 GJ per ton of crude steel [IEA, 2020, Iron and Steel Roadmap]. This highlights the importance of renewable electricity to fully exploit the environmental benefits of this route. Expanding the secondary steel route necessitates greater availability of scrap steel and broad adoption of low-carbon power generation [IEA, 2020, Iron and Steel Technology Roadmap[36]]

Steelmaking is one of the higher energy and resource intensive sectors. In 2022, 71.1 % of the global steel was produced though the traditional BF-BOF route with an average carbon intensity of 2.33 t CO_2/t of crude steel casted; the remaining 28.6% was produced by DRI-EAF and scrap-EAF route with respectively a carbon intensity of 1.37 and 0.68 CO_2/t of crude steel casted [Word Steel, 2024, World Steel In Figures 2024[37]]. These figures are different for the EU, where in 2022, 55.2% of EU steel was produced via the BF-BOF route, while the remaining 44.8% from EAF, mainly recycling scrap steel [Word Steel, 2024, World Steel In Figures 2024]. On average, the steel industry accounts for about 5% of the EU's total CO_2 emissions.

The BF-BOF route relies on imported iron ore, in fact Europe has minimal domestic iron ore mining beyond Sweden. This means that EU steelmakers are heavily dependent on imports for their primary raw materials, particularly iron ore and coking coal. Over 60% of the iron ore used in the EU is sourced from major mining economies such as Australia and Brazil (European Commission, Study on the EU's list of critical raw materials – Final report, 2020) with Brazil and Canada being the leading suppliers in 2023 (GMK Center, 2024[38]; Eurostat) Similarly, most of the coking coal is imported in the EU, primarily from Australia (24%), the United States (20%), and Russia (8%) (ICCT, *Green Steel Supply*, 2023[39]). This import reliance exposes the sector to global commodity price swings and supply risks, highlighting the importance of secure, affordable, and diversified raw material supply chains to maintain competitiveness of EU steel producers. This import reliance underscores the importance of secure raw material supply chains for competitiveness [Eurofer]. EAF-based production uses domestically collected steel scrap as its main feedstock, a more circular approach; however, the EU's scrap availability is finite, and the EU historically exported millions of tons of scrap each year, a pattern now under review to retain scrap for local use in green steel production.

4.2.2 Decarbonisation options for iron and steel industry

The iron and steel industry is among the most emissions-intensive sectors globally, and its deep decarbonisation is essential for achieving net-zero targets. A range of technological pathways is emerging to drastically reduce emissions across primary and secondary steelmaking routes. These include:

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[35] https://data.europa.eu/doi/10.2760/069150
[36] https://www.iea.org/reports/iron-and-steel-technology-roadmap
[37] https://worldsteel.org/data/world-steel-in-figures/world-steel-in-figures-2024/
[38] https://gmk.center/en/news/eu-reduced-iron-ore-imports-by-11-y-y-in-2023
[39] https://theicct.org/wp-content/uploads/2024/09/ICCT-Green-Steel-Supply.pdf

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1. **Shifting from conventional blast furnaces (BF-BOF) to Direct Reduced Iron (DRI) processes**, which use low-carbon hydrogen or natural gas to reduce iron ore and are typically coupled with electric arc furnaces (EAF). Hydrogen-based DRI, in particular, offers near-zero emissions potential when powered by renewables, and is gaining momentum in Europe with first commercial-scale plants expected before 2030.

2. **Scaling up high-quality scrap-based recycling** through electric arc furnaces (EAF), which bypass ore-based ironmaking and are significantly less carbon-intensive. Enhanced scrap availability and digital quality control are key to expanding this route in a circular economy framework.

3. **Deploying Carbon Capture, Utilisation and Storage (CCUS)** to mitigate emissions from existing blast furnaces and emerging smelting processes. While integration remains technically complex, CCUS can deliver substantial emissions reductions in the near term, especially in regions with suitable storage infrastructure.

These pathways are complemented by incremental and enabling innovations **such as partial fuel switching with hydrogen or biomass, digitalisation to improve energy efficiency**, and the development of advanced materials and circular business models. Table 3 provides an overview of the most promising low-carbon technologies for steel decarbonisation according to IEA[40], assessing their technology readiness, strategic relevance for Europe, and competitiveness potential.

Table 3. Innovative low-carbon technologies and decarbonisation measures for iron and steel sector. Source: Authors elaboration on IEA *ETP Clean Energy Technology Guide*.

Technology	TRL	Relevance and Competitiveness Potential in Europe
Hydrogen-Based Direct Reduced Iron (H_2-DRI)	7–8 (Pre-commercial Demo)	Uses electrolytic hydrogen to reduce iron ore. Enables near-zero carbon steel when powered by renewables. Europe is leading in H_2-DRI pilots (e.g. HYBRIT) and first-of-a-kind plants by 2026–2030, especially in regions with cheap clean power. Expected to dominate primary steel production by 2050, giving the EU a competitive edge in "green steel" if hydrogen costs can be lowered.
High blend of H2 in natural gas DRI	7–8 (Pre-commercial demonstration)	Process emissions can be significantly lowered by replacing part of natural gas with hydrogen produced via electrolysis powered by low-carbon electricity (see option above). Existing commercial technologies can already accommodate hydrogen blends of up to 30%

[40] International Energy Agency. (2025). *ETP Clean Energy Technology Guide*. https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide

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		without major modifications, while the feasibility of higher substitution levels is currently under investigation. Projects: Spain, Arcelormittal; Germany, Thyssenkrupp; Austria, H2Future (Voestalpine steel plant); Spain ArcelorMittal Gijon; Mexico, Tenova; Canada, Arcelormittal; China Baowu Steel Blast Furnace H2; China HBIS Hebei in Zhangjiakou City, Hebei province.
Chemical Absorption for DRI	9 (Commercial)	Chemical Absorption CO2 capture (ammine based) for direct reduction iron plants with regeneration of solvent (T range 20-150 °C). Good potential but limitation due to high cost of natural gas in several countries. Projects: United Arab Emirates in 2016, it is first commercial CCUS project integrated with natural gas based DRI, developed by bu Dhabi National Oil Company (Adnoc), Masdar and Emirates Steel Industries
Blast Furnace with Carbon Capture (BF-BOF with CCUS)	6–7 (Demo scale)	Captures CO_2 from blast furnace exhaust for storage or use. Retrofits existing assets to cut emissions ~60%. European trials (e.g. in France and Sweden) are in progress, but integration is complex. Relevant for steel hubs near CO_2 storage (North Sea) or where hydrogen may be delayed.
Smelting Reduction (e.g. HIsarna)	7 (Pilot proven)	A coal-based smelting process that produces iron from ore in a single step (bypassing coke ovens/sinter). It generates CO_2-rich off-gas suitable for capture. Piloted in the Netherlands, it can cut emissions ~20% even without CCS. Europe sees it as a potential alternative to blast furnaces, especially if coupled with oxygen and CCS (Tata Steel plans). Could use biomass or even hydrogen plasma (future variant) to further reduce CO_2.
Upgraded biomass for partial replacing injected coal in BF-BOF	9 (Commercial)	Bio-coal production through torrefaction or pyrolysis at 200-400 °C in the absence of oxygen from different types of biomass. It cannot fully replace coal and it is subject to biomass availability. Incremental innovation. Projects: Canada, AncelorMittal Dolfasco. Belgium, Torero ArcelorMittal Ghent in Belgium, large scale demonstration. Finland, SSAB Brahestad
Conversion of steel offgases to chemicals in BF	7. Pre-commercial demonstration	This technology converts waste gases from steel production such as blast furnace and coke oven gas into chemical products, effectively reusing CO_2 and delaying its release. Its climate benefit depends on the carbon intensity of displaced inputs and the current

		use of off-gases (e.g. flaring or power generation). It may also support renewable integration by providing flexible demand in chemical production processes. Projects: Germany Carbon2Chem
Iron Ore Electrolysis (Electrowinning)	5–6 (Lab to pilot)	Novel process to produce iron via electrolysis of iron ore (either molten oxide or aqueous). Promises near-zero emissions using renewable electricity. Being developed by firms like Boston Metal (molten oxide electrolysis). Europe is supporting R&D; if successful, this could be a game-changer after 2035. Not yet at industrial scale but offers long-term competitiveness by eliminating carbon entirely from ironmaking.
Carbon Capture and Use (CCU) for Off-gases	7 (Demo)	Converts steel plant waste gases (CO, CO_2, H_2 mix) into valuable products. European projects like Carbon2Chem (thyssenkrupp) and Steelanol (ArcelorMittal) ferment or catalyse CO_2-containing gases into chemicals (ethanol, fertilisers). TRL is high from a technology standpoint (demonstration ongoing), but economic viability depends on product markets. CCU can turn a liability (emissions) into revenue, enhancing competitiveness if commercialised at scale
Cross-cutting measures		
Digital Process Optimisation (Industry 4.0)	9 (Commercial)	Deployment of AI, digital twins, and advanced controls in steel production. European plants are adopting these to maximise energy efficiency, quality, and throughput. For example, AI can predict and control furnace conditions to minimise fuel use. This is fully commercial (TRL 9) and already yielding economic gains – essential for competitive operations given high energy costs in Europe. Continued digital innovation will compound efficiency and cost advantages.
Manufacturing – reducing metal forming losses ad lightweighting through additive manufacturing *(Cross-cutting measure)*	9 (Commercial)	Although not a core production process, 3D printing of metal parts and development of high-performance steel alloys are important innovations. EU steelmakers are investing in additive manufacturing to open new markets (e.g. printed steel components) and in advanced alloys that enable lighter, longer-lasting products. These innovations diversify revenue and align with circular economy goals (by extending product life and recyclability), strengthening the industry's competitive position in high-value steel segments. Projects: StaVari research project, EDAG.

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4.3 Key Enablers of Steel Competitiveness: Energy, Skills, Investment, Policy and Trade

The competitiveness of the EU steel industry is determined, as discussed in Section 2, by a combination of structural cost factors, access to affordable energy and capital, labour and infrastructure conditions, and the regulatory environment. This section identifies and analyses the key enabling and constraining factors affecting the steel sector's ability to remain globally competitive while transitioning toward climate neutrality.

4.3.1 Production Cost Structure: CAPEX, OPEX, Energy and Labour

Steel production costs are primarily driven by raw materials and energy prices (iron ore, pellets, scrap, limestone, fuels and electricity, etc) which together account for 60–80% of the total cost according to the global average value for the levelised cost of production provided by IEA for 2019 with CAPEX and fixed OPEX cover the rest of the share[41]. Electricity and gas prices are particularly important for the scarp-EAF route, while BF-BOF is more exposed to coking coal prices.

While, from the resource availability point of view, scrap steel typically costs more than iron ore but requires less energy to process, while iron ore prices follow global supply-demand dynamics. Scrap availability increases with price, as sorting and collection of steel become more economical.

Production routes differ in their energy intensity, with BF-BOF and DRI-EAF far more energy-consuming than scrap-based EAF and in their energy mix, with BF-BOF using coal and fossil fuels with DRI-EAF depending mostly on electricity use. This makes energy prices a key factor for steel competitiveness, especially in regions with high electricity or gas costs. While equipment costs are similar across countries, differences in labour, engineering, and construction costs may create significant regional variations. In this context, Europe faces higher operating costs due to expensive energy products, while China, India, and the Middle East benefit from cheaper inputs, and the US maintains a competitive scrap-based production due to the low electricity prices.

Due to high energy use in iron and steel, rising energy prices in Europe have therefore had a major impact on steel producers. The 2021–2022 increase in European natural gas and electricity costs – far higher than energy prices in regions like China or the U.S. – has reduced operating margins, already low for this sector, and undermined the cost advantage of cleaner production routes. In particular, as reported in the Draghi Report in 2024, for primary steel production, energy prices accounted for 53% of total production costs in Europe in 2022, compared to 30% in the United States and just 27% in China. For secondary steel produced via the scrap-based Electric Arc Furnace EAF route – primarily powered by electricity, but also natural gas – the energy cost share was 27% in the EU, but it was significantly lower in the US (13%) and China (12%)[42].

[41] IEA (2020), *Iron and Steel Technology Roadmap*, IEA, Paris https://www.iea.org/reports/iron-and-steel-technology-roadmap

[42] European Commission (2024), The future of European competitiveness

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These high energy prices, especially in electricity and gas, limit the cost-effectiveness of clean production routes and reduce investment availability. For example, the MIDREX direct reduction technology – which uses natural gas and can later switch to hydrogen – offers a phased transition path. However, high gas prices in Europe could delay its deployment.

According to Draghi Report, in 2023, 60% of European steel companies identified energy prices as a major obstacle to investment, over 20 percentage points more than their counterparts in the United States. According to the IEA, the EU's fossil fuel import bill reached €416 billion in 2023, equivalent to approximately 2.7% of GDP, which is **90% higher than the 2017–2021 average**, largely due to elevated prices rather than increased volumes. These growing costs place a considerable burden on the EU's economic resources, reducing its capacity to invest in infrastructure, innovation, and education that are key areas for maintaining long-term growth and competitiveness. Moreover, high natural gas and electricity prices may delay the deployment of direct reduction (DR) technology fed by natural gas. For example, the main producer of this technology, MIDREX, has already the flexibility to transition from natural gas to (green) hydrogen when it becomes more available and cost competitive. This phased approach enables early emissions reductions while preserving the option to fully decarbonise in the future through retrofit or partial reconversion to hydrogen use [43].

A structural investment challenge for EU steel

Europe's iron and steel sector is at a critical investment crossroads, facing the dual imperative of decarbonising production while remaining globally competitive. The sector must simultaneously replace ageing industrial assets and deploy new clean technologies, while operating in a capital-intensive, high-risk environment. Massive capital is needed in the coming years to adopt low-carbon technologies (like hydrogen-based steelmaking and carbon capture) and modernise aging plants, at a scale comparable to a post-war reconstruction effort.

The required effort is frequently compared to a post-war reconstruction. In fact, the 2024 Draghi report on EU competitiveness warns that reversing Europe's industrial decline will require raising the EU-wide investment rate from roughly **22% of GDP to about 27%**, an increase of nearly € 800 billion annually.

Global and EU-level investment needs

The steel industry exemplifies this challenge: on one hand, it must attract huge new investments to achieve climate targets with **global estimates provide by IEA that suggest $372 billion will be required to transform existing steel assets to near-zero emissions by 2050[40]** yet on the other hand Europe's steelmakers are struggling with eroded profits and low capacity utilisation, which affects their ability to invest as presented in the previous sections . EUROFER, the European Steel Association, has cautioned that "billions of our investments in decarbonisation are at risk, while we have to bear energy costs that are 2–3 times higher than those of our main competitors in the US and China" [EUROFER 2024].

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[43] https://www.midrex.com/tech-article/future-processing-options-for-hydrogen-dri/

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Competitiveness gap, international comparison and the EU Clean Industrial Deal

High electricity and gas prices in Europe, coupled with a stringent carbon pricing regime, increase operating costs and make investment payback periods longer, undermining the business case for new projects in the steel sector.

At the same time, global competition is intensifying**:** the United States has boosted industrial investment through measures like the Inflation Reduction Act (which provides **$5.8 billion for industrial decarbonisation**[44], nevertheless the last change in US administration can slow or reduce this commitment while China's state-backed steel companies continue to expand capacity and massively invest abroad in low-cost countries. As already mentioned, the European Commission has formulated the Clean Industrial Deal – a comprehensive strategy to support green industries to mobilise over €100 billion for clean manufacturing and create a more favourable investment environment.

4.3.2 Policy and Regulation

The EU policies and regulation for the iron and steel sectors include industry and energy legislation, circular economy initiatives, trade measures, and State aid frameworks. These instruments collectively aim to steer energy-intensive industries toward a low-carbon, competitive future while preserving their strategic role in the European economy.

Among these frameworks, the Clean Industrial Deal, already introduced earlier in this document, provides the overarching strategic direction. It reframes the EU's climate neutrality target as a driver of industrial competitiveness, setting out five key levers: affordable energy, clean technology deployment, a fair transition, resilient supply chains, and strategic autonomy. The Deal also calls for the alignment and activation of sector-specific pathways and action plans to operationalise these objectives.

The European Steel and Metals Action Plan represents the most concrete application of the Clean Industrial Deal's principles for one of Europe's most foundational sectors. It translates high-level ambitions into actionable instruments organised into six strategic pillars: access to clean energy, prevention of carbon leakage, protection of EU industrial capacities, promotion of circularity, safeguarding of quality jobs, and investment de-risking.

The Plan does not operate in isolation but is embedded within a framework structure where upstream measures (such as State aid rules, the Carbon Border Adjustment Mechanism, and energy and tax directives) condition the effectiveness of downstream initiatives (including support for Power Purchase Agreements, the use of Contracts for Difference and measures to promote secondary raw material markets). In doing so, the Action Plan consolidates and reinforces previous EU strategies such as REPowerEU, the Critical Raw Materials Act, and the Affordable Energy Action Plan, putting energy affordability and industrial competitiveness at the centre of the EU's net-zero transition.

[44] U.S. Department of Energy. (2023). *Industrial decarbonization roadmap*. https://www.energy.gov/media/280160

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The strategic logic underpinning the Steel and Metals Action Plan rests on three interdependent imperatives: restoring cost-competitiveness, unlocking low-carbon investments, and protecting the sector strategic capacity from external shocks such as trade distortions or global overcapacity. The Commission's stated goal is not merely to mitigate risks of deindustrialisation but to transform the sector's business model around resilience, sustainability, and innovation driven by new patterns of demand. One of the most cogent features of the Action Plan is its comprehensive strategy for de-risking investments in decarbonisation. The policy acknowledges that the commercial case for clean metals (i.e. green steel) remains weak under current market conditions. The so-called "scissors effect" that is high capital and operating costs combined with low or uncertain green premiums makes public intervention indispensable.

At the policy level, this is being addressed through funding and de-risking tools:

– **Direct Public Funding (CapEx and OpEx)**: €9 billion in State aid already approved for 10 steel decarbonisation projects (2022–2025); CfDs deployed across DE, FR, IT, AT, CZ, and SK; ETS Innovation Fund support.

– **Research and Innovation**: €600 million Horizon Europe call in 2026–27; RFCS reform and €150 million flagship initiative; LIFE Program support for circularity and clean processes.

– **Blended Finance and Market-shaping**: A €100 billion Industrial Decarbonisation Bank (in design phase); EIB guarantees for PPAs; CRMA-based investment pipelines for nickel, aluminium, and copper.

– **Demand-side Instruments**: Carbon footprint labels (steel 2025); public procurement criteria; CBAM reform; circular content targets under ESPR and ELV Regulation.

While these instruments form a coherent architecture, their implementation will depend on overcoming structural bottlenecks such as infrastructure development delays, PPA accounting burdens, fragmented scrap markets and delays in upscaling the demand for green industrial products. In this respect, the Plan proposes multiple flanking actions—simplified State aid conditions, anticipatory investments in grids, and standardisation of secondary metal qualities. Yet, success will hinge on national uptake and regulatory coordination, which remains uneven across EU Member States.

Integrated governance and Investment Strategy for the decarbonisation steel strategy

The evolving EU industrial strategy for steel and metals has three levels of regulation and investment mobilisation. Each level reflects a different policy logic: macro-level ambition (climate-industrial development alignment), meso-level regulatory enablers, and micro-level investment deployment. The Steel and Metals Action Plan (SMAP) sits at the operational core of this system and exemplifies the vertical integration of EU-level industrial planning.

1. Strategic Level: Clean Industrial Deal

At the top of this governance pyramid is the Clean Industrial Deal, the framework that reframes climate neutrality also as competitiveness goal. The Clean Industrial Deal is not a financial instrument per se, but rather a unifying narrative, strategy, and governance meta-framework. It sets out five levers for competitiveness: affordable energy, clean tech scale-up, fair transition, resilient supply chains, and open strategic autonomy. It explicitly identifies the steel and metals sectors as sector for balancing decarbonisation with reindustrialisation.

Within this framing, the Clean Industrial Act calls for a stronger interplay between:

- Energy market reform (electricity decoupling, PPA guarantees, energy affordability)
- Trade instruments (e.g. CBAM and anti-dumping measures)
- Public procurement (green lead markets)
- State aid flexibilities

2. Regulatory Layer: Enabling Frameworks

The Clean Industrial Act cascades into a set of enabling acts and guidelines that define the boundaries for national and EU interventions:

- Affordable Energy Action Plan (AEAP): the main goal is to lower energy input costs
- Critical Raw Materials Act (CRMA): securing upstream inputs of raw materials
- State Aid Guidelines (CEEAG & CISAF): defining conditions for aid compatibility
- Carbon Border Adjustment Mechanism (CBAM): protecting EU industries from industrial relocation risks
- REACH revision and Circular Economy Acts: unlocking scrap circularity and regulatory simplification

These instruments act as structural enablers, creating the necessary conditions but not directly generating investment in low-carbon steelmaking. Their success depends on the investment pipeline they aim to de-risk.

3. Operational Layer: The Steel and Metals Action Plan

The Steel and Metals Action Plan (2025) is the most concrete manifestation of the CID's industrial intent. It operates as a policy aggregator, integrating instruments and identifying sequencing across six strategic pillars. Investment mobilisation is central to the Plan's logic and is treated both as a policy goal and a delivery mechanism.

The Steel and Metals Plan is one of several forthcoming or existing sector-specific transition pathways under the umbrella of the Clean Industrial Deal. Similar operational frameworks are expected or underway for other energy-intensive and strategic sectors, including chemicals, each of which is developing its own targeted measures for clean technology deployment, regulation, enhanced competitiveness, circularity, and skills upgrading. Together, these operational documents form the implementation backbone of the Clean Industrial Deal's transformation logic. As of April 2025, only the Steel and Metals Action Plan and the Chemicals Transition Pathway have been formally published. Other sectoral frameworks, including those for automotive, fertilisers, and sustainable transport, are expected to be released later in 2025.

The investment architecture described across the Steel and Metals Action Plan (SMAP) and the Clean Industrial Deal includes several coordinated funding mechanisms and enabling tools:

- €9 billion in approved State aid for decarbonisation projects in the steel sector between 2022 and 2025, authorised under the Climate, Environmental Protection and Energy Aid

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Guidelines (CEEAG);

- A target of €100 billion for the Industrial Decarbonisation Bank, expected to be capitalised through proceeds from the EU Emissions Trading System (ETS) and channelled via InvestEU and national contributions;
- Project-level support from the EU Innovation Fund, alongside Horizon Europe calls dedicated to scaling up low-carbon industrial technologies, including a €600 million flagship initiative for steel and metals (2026–2027);
- Strategic project facilitation under the Critical Raw Materials Act (CRMA)
- Demand-side shaping via public procurement criteria and voluntary labelling of low-carbon steel products, supported by the forthcoming Industrial Decarbonisation Accelerator Act and the revision of the Ecodesign for Sustainable Products Regulation (ESPR).

The various instruments supporting the decarbonisation of the steel and metals sector form a vertically and horizontally integrated framework. Vertically, the Clean Industrial Deal provides the overarching narrative and direction, which is translated through the Steel and Metals Action Plan into specific sectoral initiatives. Horizontally, enabling measures across trade policy, energy regulation, State aid, and circular economy interact to form the operational environment for industrial transformation.

Energy-related directives, such as the revised Renewable Energy Directive (RED III), the Energy Efficiency Directive, the EU ETS Directive, and the Energy Taxation Directive play a critical role in shaping cost structures and investment signals for energy-intensive industries and steel manufacturing in particular. These energy-focused directives intersect with industrial, trade and competition rules, influencing everything from power purchase agreements and grid access to eligibility for subsidies. Thus, policy coherence across these domains is essential to amplify impact and to create the right conditions for industrial decarbonisation. The effectiveness of the strategy thus depends not on isolated interventions but on the quality of coordination across these domains.

The sequencing of action follows logical progression. First, policies aim to reduce investment risk through public guarantees, fiscal incentives, and regulatory simplification, principally via State aid and the Affordable Energy Action Plan. Once this foundation is in place, demand-stimulating measures such as green public procurement, labelling of low-carbon steel products, and adjustments to the Carbon Border Adjustment Mechanism are introduced to signal long-term market viability. This is followed by the scaling up of clean technologies through instruments such as the EU Innovation Fund and Horizon Europe innovation calls. In parallel, strategic autonomy is pursued by securing critical raw materials, especially nickel, aluminium, and copper, under the Critical Raw Materials Act and through improved regulation of scrap flows. Finally, the system seeks to recycle benefits by fostering lead markets that reward lower emissions and sustainable practices, ensuring that climate policy becomes economically self-reinforcing.

4.3.3 Infrastructure gaps in enabling technologies: green hydrogen and CCS

The deployment of enabling technologies such as green hydrogen and carbon capture and storage

(CCS) is fundamental for the deep decarbonisation of the iron and steel sector. However, infrastructure remains a critical barrier. The *European Hydrogen Backbone* (EHB) initiative, led by a consortium of transmission system operators (TSOs), envisions a pan-European hydrogen network of approximately 50,000 km by 2040, with 75% of the pipeline network repurposed from existing gas infrastructure[45] . While this long-term vision is technically and economically feasible, implementation is still in its early phases, and infrastructure development lags decarbonisation needs.

A core obstacle is the "chicken-and-egg" dilemma between hydrogen demand and infrastructure. Industrial users, particularly in hard-to-abate sectors like the iron and steel, are hesitant to commit to hydrogen-based technologies in the absence of reliable, cost-effective hydrogen supply. At the same time, infrastructure developers are reluctant to invest without credible long-term offtake agreements. This mutual dependency hampers investment flows and slows project implementation[46].

Regulatory complexity adds further uncertainty. The recent Delegated Act under the Renewable Energy Directive (EU) 2018/2001[47] introduces binding criteria for the definition of renewable hydrogen, including temporal and geographical correlation with renewable electricity production. While the Act provides much-needed clarity and creates a framework for certification, compliance may prove difficult in regions with limited access to low-cost, clean electricity or with grid constraints.

The CCS infrastructure faces similar bottlenecks: cross-border CO_2 transport networks remain fragmented, storage sites are unevenly distributed across Member States, and liability and permitting frameworks are still under development[48]. Without accelerated investment in infrastructure, clear governance frameworks, and strong coordination across national and EU levels, these barriers risk undermining Europe's climate targets and delaying the uptake of breakthrough technologies critical to the competitiveness and transformation of the EU steel industry.

4.3.4 Workforce and skills needed for the transition

Decarbonisation and digitalisation are driving structural changes in the steel workforce, creating demand for new competencies. Achieving climate-neutral steel production requires advanced technical skills that differ from those needed in traditional blast-furnace operations. Similarly, Industry 4.0 automation, including AI-driven process control and sensor-driven maintenance, is

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[45] European Hydrogen Backbone (EHB). European Hydrogen Backbone. (2023). Growing a pan-European hydrogen network. https://www.ehb.eu

[46] Agora Energiewende. (2021). *Making renewable hydrogen a success: Policy recommendations for scaling up hydrogen in Europe*. https://www.agora-energiewende.de/fileadmin/Projekte/2020/2020_11_EU_H2-Instruments/2021-07-08_Presentation_H2-Instruments.pdf

[47] European Commission. (2023a). *Commission Delegated Regulation (EU) 2023/1185 supplementing Directive (EU) 2018/2001 as regards the methodology for assessing greenhouse gas emissions savings from renewable fuels of non-biological origin*. https://eur-lex.europa.eu/eli/reg_del/2023/1185/oj/eng

[48] European Commission. (2023b). *Communication on Industrial Carbon Management* (COM(2023) 710 final). https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2023:710:FIN

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transforming shop-floor roles, increasing the need for digital literacy. **Digital and "green" skills have become critical**: one industry initiative notes that economic, technological and environmental developments now require *"continuously updating the qualification, knowledge and skill profile of the workforce"*[49]. However, there is a skills gap to bridge. The EU has acknowledged shortages of specialists in areas like digital engineering and clean tech, which pose a barrier to growth. . In fact, Draghi's 2024 Competitiveness Report stresses the need to *close the skills gap* as a pillar of industrial strategy. Concerted efforts are underway to upskill and reskill steel workers for the green transition – for instance, the World Steel Association within a European project has helped map out the green skills young workers will need in an increasingly electrified, low-carbon steel industry[50].

As part of these efforts, the study European Vision on Steel-Related Skills and Supporting Actions to Solve the Skills Gap Today and Tomorrow in Europe[51] emphasises the need for a highly technical, integrated approach to skills development tailored to the specific demands of the steel industry. One of the core recommendations is the creation of EU-wide monitoring tools that can forecast the evolving skill requirements based on emerging technologies and market trends. These tools would utilise advanced data analytics and modelling techniques to track the rapid changes in manufacturing processes, such as the adoption of low-carbon hydrogen-based production methods, electrification of furnace systems, and advancements in carbon capture, utilisation, and storage (CCUS) technologies. By establishing these monitoring systems, the EU could ensure that the workforce remains aligned with both current and future technological needs, reducing time lags between innovation implementation and the availability of trained personnel.

In addition, the study stresses the importance of promoting lifelong learning, with a particular focus on the technical competencies required to operate and innovate within Industry 4.0. Steel production increasingly relies on the integration of digital technologies such as AI, machine learning, predictive maintenance, and robotics to optimise production processes and improve energy efficiency. To meet these demands, the workforce must be proficient in digital tools and methodologies such as process modelling, real-time data analysis, and automated decision-making systems. Therefore, an essential element of lifelong learning will be ensuring that workers are equipped with both foundational technical knowledge and the ability to adapt to rapidly evolving technologies. Moreover, cross-sectoral collaboration is encouraged to enhance the transferability of skills, especially in digital and green technology applications.

Another key technical aspect highlighted in the study is the expansion of on-the-job training programs, which play a pivotal role in translating theoretical knowledge into practical expertise. These programs should incorporate training modules that reflect the specific requirements of the latest technologies in the steel industry, including the operation of new low-carbon processes,

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[49] *EUROFER. (2024). European Steel Skills Agenda (ESSA). https://www.eurofer.eu/issues/sustainability/social-affairs/european-s)*
[50] Fant, S. (2024, July 15). *Decarbonising steel: An interview with Andrew Purvis (World Steel Association)*. Renewable Matter. https://www.renewablematter.eu/en/decarbonising-steel-an-interview-with-andrew-purvis-world-steel-association
[51] European Commission: Executive Agency for Small and Medium-sized Enterprises, Centro Sviluppo Materiali S.P.A, Intrasoft International, RINA Consulting, Valeu Consulting, & White Research. (2020). *European vision on steel-related skills and supporting actions to solve the skills gap today and tomorrow in Europe*. Publications Office of the European Union. https://data.europa.eu/doi/10.2826/2092

such as hydrogen Direct Reduced Iron (H_2-DRI) and Electric Arc Furnace (EAF) systems optimised for scrap-based recycling. In addition, training programs should include modules on the integration of digital systems for real-time monitoring and control, which are essential for enhancing the efficiency and sustainability of steel production processes. The study also points out that the increasing complexity of industrial processes calls for a stronger emphasis on simulation-based training. By using virtual environments to simulate steel production processes, workers can practice complex tasks and decision-making without the risks associated with live production. Furthermore, the application of augmented reality (AR) and virtual reality (VR) in training could improve hands-on learning, allowing workers to experience real-time scenarios and adjust as needed. By addressing these recommendations, developing EU-wide skills monitoring systems, promoting lifelong learning, incorporating advanced digital competencies, and expanding on-the-job training with a focus on cutting-edge technologies, Europe can ensure that its steel industry is well-positioned to meet the challenges of decarbonisation and digitalisation.

4.4 Summary: key factor for European Steel production competitiveness

The competitiveness of the EU iron and steel industry is being reshaped by a set of interdependent pressures and opportunities emerging from global market dynamics, rising energy and input costs, and the urgent need to decarbonise industrial production.

Firstly, **Europe's cost disadvantage**, particularly in relation to energy prices, has significantly affected operating margins and the economic feasibility of both conventional and low-emission steel production routes. In 2022, for instance, primary steel production in the EU faced energy costs representing over half of total production costs, compared to significantly lower shares in the US and China.

Secondly, the **low-cost imports** from China and other regions have depressed prices across the EU market. The expiration of safeguard measures and new potential US tariffs in April 2025 are further constraining export opportunities for European steel producers, undermining their ability to compete internationally.

At the same time, **investment in decarbonisation** is being delayed or suspended, as high capital costs and regulatory uncertainty disincentivise long-term commitments and large capital investment. Despite technological progress in low-carbon steelmaking, including the emergence of hydrogen-based DRI and CCUS-ready solutions, companies remain cautious in the absence of stronger industrial policy signals and financial support for decarbonisation.

In terms of **resource dependency,** the EU continues to rely heavily on imports of iron ore and coking coal, while domestic scrap that is essential for EAF-based, low-emission steelmaking, is finite and historically underutilised due to exports.

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5 Cement industry

The cement sector is a cornerstone of the global construction industry, providing the essential binding material used in concrete, the most widely used man-made material in the world. Cement enables the development of critical infrastructure such as roads, bridges, buildings, and water systems, making it fundamental to economic growth and urbanisation. However, cement production is also one of the most energy- and carbon-intensive industrial processes, driven largely by the calcination of limestone and high-temperature kiln operations. As a result, the sector faces increasing scrutiny and pressure to decarbonise while continuing to meet growing global demand.

The cement industry is vital to the construction sector, providing the foundational material for the construction of buildings, infrastructure, roads and more. The cement industry has evolved significantly over centuries, transforming from ancient construction materials to a cornerstone of modern infrastructure. The late 19th and early 20th centuries saw the industrialisation of cement production, with the introduction of rotary kilns and advancements in kiln technology, leading to increased production capacities and efficiency. Post-World War II, the cement industry expanded globally, driven by the urbanisation and infrastructure development. Major companies emerged, consolidating operations across multiple countries.

This cement industry is the third-largest industrial energy consumer (IEA, 2018[52]) and is responsible for about 5%-8% of global CO_2 emissions every year[53], making it a significant contributor to climate change[52]. Companies are investing in alternative materials, carbon capture technologies and energy-efficient processes to reduce emissions from cement production.

This sector faces economic challenges, including fluctuating raw material costs and energy prices, as well as unpredictable market demand driven by the cyclical nature of construction activity, infrastructure development and shifting industry trends. Stricter environmental regulations and the need to meet net-zero emissions targets are pushing the industry toward more sustainable practices. About 61% of large, publicly traded cement companies consider climate change as a key option for their strategic assessment[54].

In Europe, CEMBUREAU, the European Cement Association, in 2020 had set a 30% CO_2 emissions reduction target on cement and 40% down the overall value chain compared to 1990 values by 2030. These values were revised in 2024 to 37% and 50% respectively to align with the new EU climate targets for 2030. The EU industry's 2040 ambitions are 78% and 93% correspondingly to reach the net zero target in 2050[55].

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[52] https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry
[53] D.Cheng, et al, "Projecting future carbon emissions from cement production in developing countries", https://doi.org/10.1038/s41467-023-43660-x
[54] https://reports.weforum.org/docs/WEF_Net_Zero_Industry_Tracker_2024_Cement.pdf
[55] https://cembureau.eu/media/ulxj5lyh/cembureau-net-zero-roadmap.pdf

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5.1 Global cement market and EU position

The cement sector has a large economic impact due to its long and diverse supply chain and in 2020 it contributed 5.4% of global Gross Domestic Product (GDP) and 7.7% of world employment[56]. Globally, the industry registers the highest emissions per revenue dollar among similar, hard-to-abate sectors, producing 6.9 kg of CO_2 per dollar compared to 1.4 kg for iron and steel, and 0.8 kg for oil and gas (2017)[57,58].

The global cement industry is dominated by a few key players, with some of the largest producers based in both developed and emerging economies. The world production of cement in 2022 was estimated at approximately 4.1 billion tonnes[59] and the largest cement-producing regions/countries are China, India, EU, Vietnam, and the United States. Most of the increased production up to now has been driven by China's industrialisation and infrastructure build-up, but as demand drops there, future increases are expected to come from other rapidly developing economies, including India, Southeast Asia, and Sub-Saharan Africa. China leads the global cement production market by a large margin (52%)[60], contributing more than half of the world's cement production due to its infrastructure development and rising construction sector that boosts domestic demand for cement. India is the second largest cement producer globally, contributing more than 8% of the world's cement production. The country's cement sector is predominantly driven by the private sector, which controls around 98% of the market with the remaining portion under public ownership. As of 2023, India's cement production reached about 374 million tons (MT) with a 6,83% year on year growth[61]. The large infrastructure investments and residential projects in this country suggest that cement demand and production will grow in the upcoming years.

Cement is a critical sector in the European Union, both economically and strategically. In 2022, the cement industry in the EU produced about 175 million tonnes of cement, corresponding to 4.3% of the global production. The EU cement sector generated about 7.6€ billion of Gross Value Added (GVA) in 2022 and employs about 35,000 direct workers and the sector results in approximately 365,000 indirect jobs (Statista, Eurostat) with 200 integrated cement plants are located in the EU (CEMBUREAU).

Table 4. Cement production of G20 + permanent invitee Spain[62] (Million tonnes)

Country	2001	2005	2010	2015	2016	2017	2018	2019	2020	2021	2022
China	661,0	1079,6	1881,9	2350,0	2403,0	2316,3	2176,7	2300,0	2376,9	2362,8	2118,0
India	102,9	146,8	220,0	270,0	289,3	285,0	327,7	320,0	290,0	351,6	387,6
EU	**225,6**	**251,1**	**192,1**	**167,2**	**169,1**	**175,1**	**179,8**	**182,1**	**171,5**	**182,5**	**175,8**

[56] https://www.ifc.org/content/dam/ifc/doc/mgrt/202008-covid-19-impact-on-cement-industry.pdf
[57] https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement
[58] https://www.ifc.org/content/dam/ifc/doc/mgrt/ifc-strengthingsustainability-cement-web.pdf
[59] https://cembureau.eu/media/dnbf4xzc/activity-report-2023-for-web.pdf
[60] https://www.statista.com/statistics/267364/world-cement-production-by-country/
[61] https://www.ibef.org/industry/cement-presentation
[62] https://cembureau.eu/media/pnmjo3ko/cement-production-2022-table.pdf

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Country	2001	2005	2010	2015	2016	2017	2018	2019	2020	2021	2022
USA	88,9	99,4	65,2	83,4	84,7	86,1	87,8	88,6	89,3	93,0	93,0
Brazil	39,4	39,2	59,1	72,0	57,6	54,0	53,5	53,4	61,1	65,9	63,6
Turkey	35,9	42,8	62,7	71,4	75,4	80,6	72,5	57,0	72,3	78,9	73,7
Russian Federation	28,7	49,5	50,4	69,0	55,0	54,7	53,7	54,1	55,8	60,1	60,8
Indonesia	31,1	36,1	39,5	65,0	61,3	68,0	70,8	64,2	64,8	69,2	69,5
South Korea	52,0	49,1	47,4	52,0	56,7	57,9	55,0	56,4	47,5	50,4	51,1
Japan	79,5	72,7	56,6	55,0	53,4	60,8	60,1	58,3	51,1	50,2	48,9
Saudi Arabia	20,0	26,1	42,5	55,0	55,9	47,1	42,2	42,2	53,4	53,7	52,6
Mexico	33,2	38,1	34,5	39,8	42,4	42,8	42,8	47,5	41,9	45,2	43,9
Germany	32,1	31,9	29,9	31,1	32,7	34,0	33,7	34,2	35,5	35,0	32,9
Italy	39,8	46,4	34,4	20,8	19,3	19,3	19,3	19,2	18,1	20,6	18,8
France	19,1	21,7	18,0	15,6	15,9	16,9	16,5	16,5	16,7	17,5	16,8
South Africa	8,4	12,1	10,9	14,0	13,6	13,2	12,5	12,4	13,3	13,4	13,0
Canada	12,1	13,5	12,4	12,5	11,9	12,7	13,3	13,4	13,0	14	13,7
Argentina	5,5	7,6	10,4	12,2	10,9	12,0	11,8	11,5	9,9	12,1	13,0
United Kingdom	11,9	11,6	7,9	9,6	9,4	9,4	9,2	9,1	8,0	9,0	8,4
Australia	6,8	9,1	8,3	9,3	10,0	10,0	9,8	10,0	9,6	9,6	10,1
Spain	40,5	50,3	26,2	15,1	15,0	16,1	16,6	17,4	16,2	18,6	18,5

Cement is a heavy and bulky product and transportation costs over long distances are expensive relative to the value (low-value, high-volume commodity). Land transportation costs are substantial, and a common saying was that cement could not be viably hauled beyond 200 to 300 km (road transport); 10€ per tonne for every 100km by road and around 15€ per tonne to cross the Mediterranean Sea[63] - average market price for cement in 2017 was ~ 60€ per tonne[64]. Bulk maritime shipping has transformed the economics of cement transport. While trucking cement more than 200–300 km remains costly, it is now cheaper to ship 35,000 tonnes of cement across the Atlantic Ocean than to haul the same amount 300 km by truck. This shift has opened the door for intercontinental trade in cement and clinker, especially from regions with surplus production or lower manufacturing costs[65].

Global cement trade remains relatively modest[66,67] highlighting the sector's strong domestic orientation and high transportation costs compared to other industrial products. The EU has traditionally been a net exporter of cement and consistently exports more cement than it imports maintaining a positive trade balance in the cement sector (Imports 2022: 10.18 million tonnes, Exports 2022: 11.65 million tonnes, Imports 2023: 9.33 million tonnes, Exports 2023: 10.88 million

[63] https://lowcarboneconomy.cembureau.eu/where-is-cement-used/
[64] https://cembureau.eu/media/l0on3hdn/co2-costs-in-eu-cement-production-july-2021.pdf
[65] https://cembureau.eu/about-our-industry/key-facts-figures/
[66] https://www.europarl.europa.eu/RegData/etudes/STUD/2020/652717/IPOL_STU(2020)652717_EN.pdf
[67] https://oec.world/en/profile/hs/cement

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tonnes – Eurostat). Approximately 5%-7% of European production is traded in external markets[68], with major export markets including the UK and the USA. In 2023, Member states of the EU accounted for nearly 20% of global cement exports in monetary terms []. Consistent exports highlight the EU's significant role in the global cement market. The overall cement consumption in the EU region in 2022 was 163.4 Mt[69] (~93% of domestic production) with Member States experiencing different consumption evolution.

The cost structure of cement production is shaped by its high-energy intensity, raw material requirements, and capital-intensive infrastructure. The European Union's (EU) cement industry is capital-intensive, with significant investments required for plant construction and modernisation. Estimates suggest that establishing a new cement plant costs approximately €150 million per million tonnes of annual capacity. Additionally, the total investment for a new cement plant can equate to around 30 years of turnover, underscoring the industry's substantial capital requirements[70].

In recent years, EU cement producers have been channelling substantial capital into decarbonisation initiatives. For instance, Heidelberg Cement allocates €100 million to €150 million annually for conventional CO_2 reduction projects, integrated within its overall capital expenditure plans. On average, these decarbonisation investments represent about 20% of large European cement companies' yearly maintenance capital expenditures.

5.2 Cement production

Cement is a fine powder that is used as a binder, setting and hardening when mixed with water to hold construction materials together. Cement plants are generally situated near natural materials such as limestone, marl, or chalk, which are sourced from quarries to supply calcium carbonate. Small quantities of additional materials like iron ore, shale, clay, or sand may be required to provide the necessary mineral ingredients needed to produce clinker[71].

As cement production requires large quantities of limestone, clay, and other minerals, plants are typically located near quarries to reduce transport cost of these heavy materials.

The key component of cement is clinker, which is typically ground with gypsum to control the setting time, along with other possible additives such as blast-furnace slag, silica fume, pozzolana, fly ash, burnt shale or limestone, depending on the type of cement. Clinker is essentially a mixture of limestone and minerals that have been heated in a kiln, undergoing chemical reactions due to the intense heat. The various stages of cement production are shown in Table 5.

Table 5. Manufacturing stages of cement production

No	Stage	Process
Clinker Production		

[68] https://cembureau.eu/media/3z1p4m5c/eu-cement-industry-trade-statistics-data-06-2023-edit-09-2023.pdf
[69] https://cembureau.eu/media/dnbf4xzc/activity-report-2023-for-web.pdf
[70] https://cembureau.eu/about-our-industry/key-facts-figures/
[71] https://cembureau.eu/media/wm0jmdwl/cementmanufacturing.pdf

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1	Raw materials extraction[72] and preparation	The raw materials are quarried, crushed[73] and then ground into a fine powder[74]. They are then blended to maintain the necessary chemical composition.
2	Preheating and calcination	The raw materials are preheated[75] to around 900ºC in a preheater, which helps to reduce fuel consumption by using waste heat from the kiln. In the calciner, the material undergoes a chemical transformation (calcination), where calcium carbonate ($CaCO_3$) decomposes into calcium oxide (CaO) and CO_2.
3	Clinker Formation in the Kiln	The preheated materials enter the rotary kiln[76], a large cylindrical furnace where temperatures reach about 1450ºC[77]. Inside the kiln, the materials melt and form new compounds, resulting in the formation of clinker, small gray pellets that are the main component of cement.
4	Cooling and Storage	The clinker is cooled[78] quickly using air in a clicker cooler, then stored for further processing. Cooling stabilises the clinker, making it ready for grinding.
Cement Production		
5	Grinding and adding Gypsum[79]	The cooled clinker is ground into a fine powder with a small amount of gypsum (5%), which regulates the cement's setting time. The resulting product is ordinary Portland cement (OPC) which is stored in silos before being packaged for distribution.
6	Blending *(Cement-to-clinker ratio)*	Cement can also be combined with other finely ground mineral materials, such as significant amounts of slag, fly ash, limestone, or other substances, to partially replace the clinker, often resulting in a substantial reduction in CO_2 emissions.
7	Packing and Distribution[80]	The cement is then packed in bags or stored in bulk for shipment to various construction projects and industrial sites.

[72] Limestone, clay, and other materials are extracted from quarries. The selection of these materials is crucial since they determine the quality and properties of the cement. Quarrying is energy-intensive and can lead to significant environmental degradation. Cement manufacturers are increasingly looking at sustainable mining practices to minimise their footprint.
[73] Large chunks of extracted materials are crushed to ensure uniformity and ease of processing. This pro-homogenisation ensures that the material blend remains consistent, which is essential for quality control in subsequent steps.
[74] Materials are finely ground to a powder to prepare them for blending. This grinding process is energy-intensive and has a large carbon-footprint, prompting innovations in grinding technology for energy efficiency.
[75] Blended raw materials are preheated to start chemical reactions that are completed in the kiln. Preheaters reduce energy consumption by using waste heat from the kiln, improving overall process efficiency.
[76] Raw materials are heated at very high temperatures (around 1450oC) forming 'clinker' which is the key component of cement. This step is responsible for the majority of CO2emissions in cement production due to both the fuel combustion and chemical decomposition of limestone (calcination). Low-carbon alternatives are being developed, such as substituting a portion of clinker with other materials or using alternative fuels like biomass.
[77] Mindess, S. and Young, J.F. (1981). *Concrete*. Prentice-Hall, Inc. Englewood Cliffs, NJ
[78] Rapid cooling stabilises the clinker phase, essential for ensuring cement quality. Cooling systems aim to recover waste heat for reuse in other parts of the plant.
[79] Gypsum is added during grinding to control cement setting time.
[80] Efforts to reduce emissions and costs in transport are notable, with some companies exploring carbon-neutral options for distribution.

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In cement manufacturing, four main production methods are used: the dry process, semi-dry process, semi-wet process, and wet process. Among these, the dry process is the most energy-efficient and environmentally favourable, consuming significantly less energy and resulting in much lower CO_2 emissions compared to wet and semi-wet methods. Globally, the dry process has become the dominant production route; however, older plants in developing regions continue to operate using wet-based processes. Wet kilns, associated with the wet and semi-wet methods, have been largely phased out in the EU due to strict climate and energy efficiency regulations.

Clinker production is a highly CO_2 and energy-intensive process and cement production is linked to approximately 7% of total anthropogenic carbon dioxide emissions. The production of clinker, thus cement, generates both combustion emissions and industrial processes emissions. The transformation of limestone into clinker involves a chemical reaction, the decarbonation of limestone (calcination), which releases CO_2 and accounts for approximately 50%-60% of total emissions from cement manufacturing (process emissions). This reaction requires extremely high temperatures, achieved by combustion of fuels (typically fossil fuels), which in turn generates thermal CO_2 emissions, contributing an additional 30%-35% of the industry's overall emissions (combustion emissions). The remaining 10%-15% is associated with indirect emissions, mainly from electricity consumption and the production and transport of raw materials[81,82,83].

Cement production is also highly energy-intensive: producing one tonne of cement typically requires between 2.5 and 5.5 gigajoules (GJ) of thermal energy, depending on the cement type and production process, along with approximately 110 kWh of electricity[84]. As of 2022, fossil fuels dominate the thermal energy mix used for cement production with a share of 90%, followed by bioenergy and renewable waste, and non-renewable waste with 4% each respectively[85].

Energy costs are the largest cost driver for cement manufacturers, typically accounting for 30%-40% of total production costs[86]. With the growing impact of carbon pricing mechanisms, e.g., EU ETS, the cost burden is expected to rise, especially for clinker producers, as calcination emissions are largely unavoidable and represent a direct liability under carbon markets. On average, cement manufacturers emit around 5,415.1 tonnes of CO_2e per $1 million of revenue[87].

5.2.1 Decarbonisation routes

Various associations and institutions are actively engaged in advancing the decarbonisation of the cement sector. The European Cement Association, CEMBUREAU, responded to the EU Green Deal with the Carbon Neutrality Roadmap 2050, first published in 2020 and updated in 2024 as the Net Zero Roadmap. At the global level, the Global Cement and Concrete Association (GCCA) regularly

[81] https://www.ifc.org/content/dam/ifc/doc/mgrt/ifc-strengthingsustainability-cement-web.pdf
[82] https://liftoff.energy.gov/industrial-decarbonization/low-carbon-cement/
[83] https://cembureau.eu/media/qeohlghe/240305-cembureau-position-faq-on-clinker-substitution.pdf
[84] A.Mokhtar, M.Nasooti, A decision support tool for cement industry to select energy efficiency measures, Energy Strategy Reviews, 2020, https://doi.org/10.1016/j.esr.2020.100458.
[85] https://www.iea.org/energy-system/industry/cement
[86] https://op.europa.eu/cs/publication-detail/-/publication/07d18924-07ce-11e8-b8f5-01aa75ed71a1
[87] https://www.spglobal.com/esg/insights/featured/special-editorial/decarbonizing-cement-how-eu-cement-makers-are-reducing-emissions-while-building-business-resilience?

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publishes progress reports on the sector's path to net zero. Core decarbonisation options – targeting emissions reductions both from fossil combustion and industrial processes- and circular economy strategies in the cement industry (CEMBUREAU, GCCA, IEA) include:

- **Thermal/Energy efficiency**: the objective is to improve energy use during the production of cement (upgraded kilns, preheaters, heat recovery, digital optimisation), thus reducing fuel consumption and related thermal CO_2 emissions. (target – combustion emissions)
- **Fuel substitution/Alternative fuels**: traditionally used fossil fuels are replaced with alternative energy sources, such as biomass and pre-processed waste. However, this substitution may lead to a decrease in the thermal energy efficiency, as alternative fuels may have different energy densities or combustion characteristics compared to conventional fossil fuels. (target – combustion emissions)
- **Decarbonated raw materials (circularity and waste valorisation)**: the use of decarbonated materials (e.g., industrial by-products, waste concrete fines) that already contain calcium oxide bypasses the calcination process and the related emissions. (target – combustion and process emissions)
- **Innovations (use of hydrogen and kiln electrification)**: exploration of new technologies to reduce thermal emissions; hydrogen as a clean fuel alternative to fossil fuels in kilns, develop electric kilns powered by renewable energy. (target – combustion emissions)
- **Carbon Capture**: Capture CO_2 emission from the production process and either store them or convert them into useful products. (target – process emissions)
- **Clinker substitution and novel clinkers** (Supplementary cementitious materials): reduce the amount of high-emission clinkers used in cement production, which accounts for almost 90% of total emissions of cement production. Novel cements have significant potential, but face barriers in standards, durability testing, and market acceptance. (target – combustion and process emissions)

Digitalisation presents a potential solution to the cement industry's future challenges, enabling a transformation in plant operations and maintenance while accelerating decarbonisation. AI-driven advanced process control systems could optimise fuel use, kiln performance, and emissions, contributing to a significant reduction in the industry's carbon footprint[88]. Predictive maintenance, powered by IoT sensors, may reduce downtime and operating costs by identifying potential issues before they occur. Digital twins could simulate entire plant operations, facilitating continuous process improvement and real-time optimisation[89]. These digital innovations hold the potential to enhance efficiency and guide the cement industry toward a sustainable and competitive future.

5.2.1.1 Clinker substitution

One of the most promising and technology-ready measures for the decarbonisation of the cement

[88] https://www.mckinsey.com/industries/chemicals/our-insights/artificial-intelligence-helps-cut-emissions-and-costs-in-cement-plants#/

[89] https://www.sciencedirect.com/science/article/pii/S2667305325000420

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industry is clinker substitution. Types of cement, which differ in terms of clinker content and alternative materials, have been classified and standardised by various national and international standards organisations (e.g., ASTM International, EN). The European classification follows the EN 197-1:2020 standard, extended by the EN 197-5:2020, and the main types of cement are shown in Table 3 along with information regarding the clinker content and the related emissions.

Table 6. European standardisation of cement types/products

Cement Type	Clinker Content	Carbon Footprint[90]
CEM I (Portland cement)	95-100% (EN 197-1)	803 $kgCO_2eq/ton$
CEM II (Portland-composite cement)	65-94% (EN 197-1) 50-64% (EN 197-5)	683 $kgCO_2eq/ton$
CEM III (Blast furnace cement)	5-64% (EN 197-1)	442 $kgCO_2eq/ton$
CEM IV (Pozzolanic cement)	45-89% (EN 197-1)	-
CEM V (Composite cement)	20-64% (EN 197-1)	-
CEM VI (Composite cement)	35-49% (EN 197-1)	-

The average clinker-to-cement ratio in the EU was 77.3% (CEMBUREAU) in 2021- 0.6% reduction compared to 2020, (global average in 2021: 70%[91]) and the European target is to reach a 60% ratio by 2050.

The EU's marginally higher ratio compared to the global average can be attributed to several factors. Limited availability of Supplementary Cementitious Materials (SCMs) (e.g., less fly ash due to the phase-out of coal-fired power plants, variable slag availability depending on steel production) means that the raw material base for replacing clinker is more constrained than in regions with ongoing coal/steel activity. Furthermore, the European construction sector often follows stringent performance standards and requires high-performance cement, which can restrict the extent to which clinker can be substituted with SCMs without compromising quality[92].

5.3 Modernising Europe's Cement Industry

Decarbonising the cement sector presents unique challenges compared to other energy-intensive industries. Unlike steel or chemicals, cement production releases a large share of CO_2 through the calcination process, emissions that cannot be avoided by switching energy sources alone. While other sectors can lean more heavily on electrification, feedstock substitution, or circular economy practices (like scrap recycling), cement production has limited decarbonisation alternatives. As a result, carbon capture technologies are not just a complementary solution but a critical requirement. Moreover, the localised nature of cement production complicates large-scale

[90] Environmental Product Declaration (EPD) according to EN 15804 and ISO 14025 (CEMBUREAU)
[91] https://www.iea.org/energy-system/industry/cement
[92] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02011R0305-20241117

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infrastructure deployment, making the path to decarbonisation more complex and capital intensive than in other EIIs. According to the IEA Cement Technology Roadmap, achieving the Reference Technology Scenario (RTS) would require cumulative additional investments of USD 107–127 billion globally by 2050. To fully realise the 2°C Scenario (2DS) vision over the same period, investment needs would rise to approximately USD 176–244 billion.

Achieving net zero emissions in the EU cement sector by 2050 will require substantial financial commitment across various decarbonisation levers and clean technologies infrastructure (e.g., CO_2 transport and storage networks, integration of renewable sources). According to CEMBUREAU, cumulative investments of approximately €40–50 billion will be needed for the decarbonisation of the EU cement sector, with the bulk of the capital outlays expected before 2040. These costs reflect the transformation of the industry's production processes and infrastructure to align with decarbonisation targets.

In addition to financial investments, the transition to a net-zero cement industry will also impact labour dynamics. The adoption of new technologies and processes will necessitate workforce reskilling and training, particularly in areas such as engineering, digital operations, and environmental management. While automation and digitalisation may reduce labour intensity in some production steps, the shift towards sustainable practices is expected to create new job opportunities, especially in construction and infrastructure deployment related to CO_2 transport and storage.

5.3.1 Regulatory framework & Roadmap

In addition to the general regulatory frameworks affecting all energy-intensive industries (as outlined in Section 3.5.2), the EU cement industry is subject to several sector-specific policies that guide its decarbonisation efforts. The Cement, Lime, and Magnesium Oxide BREF[93] defines Best Available Techniques (BAT) for reduction of emissions, two options: energy efficiency, and the use of alternative fuels. The sector's Net Zero Roadmap, developed by CEMBUREAU, outlines alternative pathways to achieve climate neutrality by 2050, including carbon capture, clinker substitution, and low-carbon cement production. Unlike many other energy-intensive sectors, cement is less dependent on international trade due to its low value-to-weight ratio and high transport costs, making it more domestically oriented and less exposed to international competition, global tariffs and trade distortions. Policies such as the EU Taxonomy for Sustainable Activities and the Renewable Energy Directive (RED III) further support the industry's green transition by steering investment and energy sourcing toward sustainable solutions.

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[93] https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/CLM_Published_def_0.pdf

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6 Chemicals industry

The chemical industry comprises a wide variety of production processes and products, from basic inorganic compounds to high-value specialty and consumer chemicals. This industry includes pillars for the world modern society that is ammonia production which synthesis is the basis for all the nitrogen fertilisers that make possible feeding of the around 8 billion people living today in our planet[94]. Chemicals are also essential inputs for nearly all other sectors, manufacturing, construction, healthcare, and consumer goods.

The value chain of the chemicals industry is vast and complex, and the sector's production ranges from basic chemicals and industrial gases to specialty chemicals, pharmaceuticals, agrochemicals, and consumer products like detergents and cosmetics. This diversity makes it one of the most interconnected and influential industrial sectors in the worlds.

Moreover, chemicals will play a pivotal role in supporting Europe's pathway to climate neutrality and the development of a circular economy. As foundational components in nearly all manufactured goods, they offer solutions to lower the carbon footprint of materials through innovation across the value chain. Advances in chemical processes enable more energy-efficient production methods, while breakthroughs in mechanical and chemical recycling technologies help recover resources and extend material lifespans. Moreover, the use of high-performance additives contributes to the durability and reusability of products, reducing overall resource intensity. In this way, the chemical sector not only underpins industrial decarbonisation but also acts as a key enabler of more circular and sustainable production models across the European economy.

However, the future of the industry in Europe is at a critical juncture. In December 2024, the European Chemical Industry Council (CEFIC) issued an urgent call to the incoming European Commission to adopt bold measures that restore the region's industrial competitiveness [95]. Without decisive policy action, CEFIC warned, Europe risks further plant closures, job losses, and a long-term erosion of its industrial base. A renewed industrial strategy is therefore essential and not only to enable the green and digital transition of the chemical sector, but also to safeguard its contribution to Europe's strategic autonomy and innovation capacity.

This section provides an overview of the sector at global and EU level in terms of market position, production and trade (Section 6.1), technological routes and decarbonisation options (Section 6.2) and the key factors for enabling competitiveness of this industry in Europe (Section 6.3) based on the review of the most recent reports on this sector with focus on EU.

The main source of this section for the European figures is the most updated report published by CEFIC in 2025, *The competitiveness of the European Chemical Industry* and

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[94] Smil, V. (2022). How the world really works: A scientist's guide to our past, present and future [Review of the book How the world really works, by V. Smil]. Population and Development Review, 48(4), 989–991. https://doi.org/10.1111/padr.12510

[95] Cefic. (2024, December 1st). *Cefic calls on new College of Commissioners to take urgent and bold action to secure Europe's industrial future*. https://cefic.org/news/cefic-calls-on-new-college-of-commissioners-to-take-urgent-and-bold-action-to-secure-europes-industrial-future/

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Eurostat (CEFIC, 2025)[96] .

6.1 Market position, production and trade

6.1.1 Global and EU chemicals production: main highlights

According to IEA, the global chemicals sector remains one of the most energy-intensive industries, reflecting the scale and diversity of chemical production worldwide. While overall demand for primary chemicals has increased significantly over the past decades, recent years have shown diverging trends across regions and product groups. In 2022, following the post-pandemic surge in 2021, global production slowed, partly due to the energy crisis. Europe, in particular, faced sharp setbacks: ammonia output declined in response to high natural gas prices, and the production of high-value chemicals stagnated, alongside other mature economies such as Japan and Korea. In contrast, China has solidified its position as the dominant global player, accounting for 30% of ammonia and nearly 60% of methanol production[97]. Together with the United States and the Middle East, these regions now produce the majority of high-value chemicals, leaving the European Union with a diminishing share in global output. These developments underscore the competitive pressures facing European producers, especially in energy- and feedstock-sensitive segments of the industry[83].

The EU chemical industry is the second largest in the world after China, accounting for around 14% of global chemical sales in 2022[82]. The chemical sector plays a crucial role in Europe's manufacturing landscape, accounting for approximately 5–7% of total manufacturing turnover. It comprises around 31,000 firm of which 13,000 monitored by the European Environmental Energy (Figure 5), with small and medium-sized enterprises (SMEs) making up 97% of the industry[82].

[96] Cefic & Advancy. (2025). *The competitiveness of the European chemical industry*. European Chemical Industry Council (Cefic). https://cefic.org/app/uploads/2025/01/Cefic-Advancy-study-The-Competitiveness-of-the-European-Chemical-Industry.pdf
[97] https://www.iea.org/energy-system/industry/chemicals

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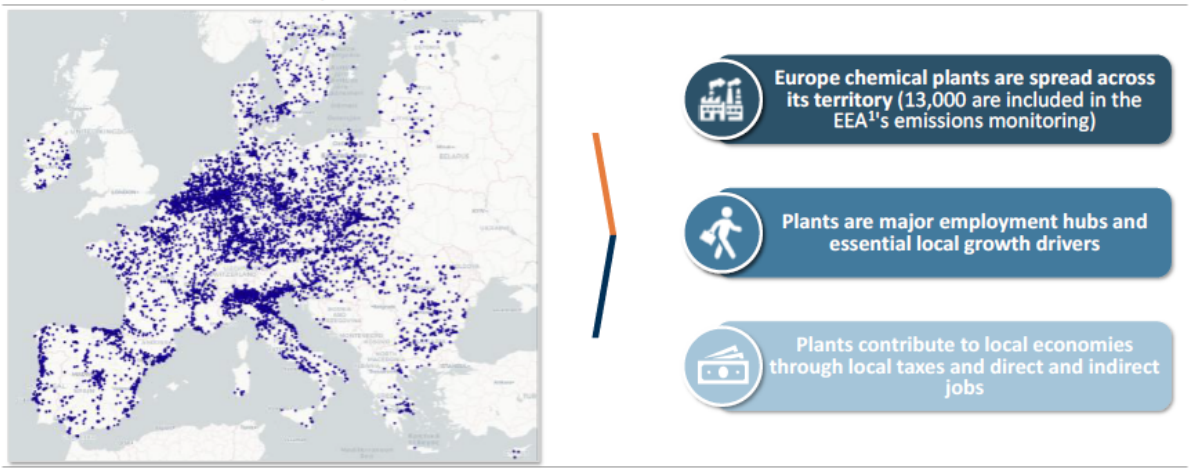
Chemical industrial sites tracked by the EEA, 2023



● European chemical sites tracked by the European Environment Agency (EEA)

Note: 13,000 companies are monitored in terms of emissions by the EEA out of 31,000 companies in Europe

Sources: EEA, Advancy analysis

Figure 5. European chemical sites in Europe in 2023. Source CEFIC, 2025

The EU chemicals industry plays a central role in the industrial economy, supplying nearly all sectors, while only a fraction of its output (combined with pharmaceuticals) reaches final consumers, the bulk goes to manufacturing, agriculture, and services. It acts as a critical link in the value chain, transforming raw materials into tailored inputs for its own operations and for downstream users. This interdependence drives innovation both within the sector and across customer industries. A strong chemical manufacturing base remains essential for Europe's overall industrial competitiveness. One reason the industry has maintained this base is the recent recovery of manufacturing activity in parts of the EU. Close proximity between chemical producers and their clients brings mutual benefits. Chemical distributors, as the final link in the chain, also support innovation uptake and promote the safe use of chemicals, particularly among SMEs.

While global production has been steadily growing, driven by demand from agriculture, health, and manufacturing, the EU share in the global market has been decreasing due to rising costs and competition from 27% in 2002 to 14% in 2022 [82] even if the sales more than double from 363 in 2002 to 760 Euro billions in 2022 as presented in Figure 6.

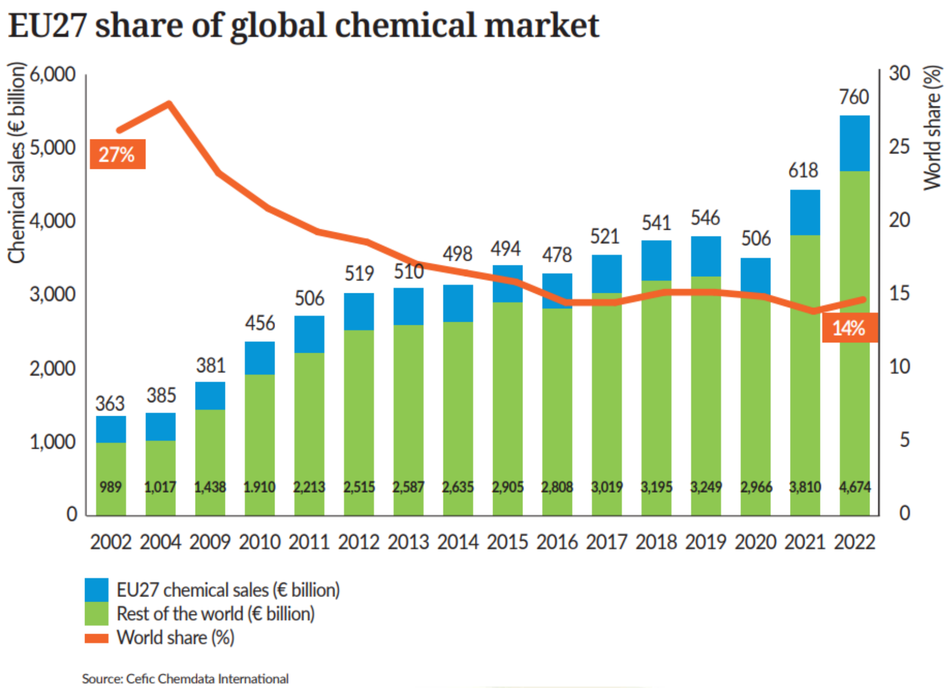


Figure 6. EU27 Share of global chemical market. Source CEFIC 2025

According to Eurostat, the EU produced 218 million tonnes of industrial chemicals in 2023, while apparent consumption reached 227 million tonnes[98]. This reflects a year-on-year decline of 13% in production and 14% in consumption, the lowest levels recorded since 2009. Moreover, 167 Mt of these were classified as hazardous to human health and 68 Mt as hazardous to the environment [99].

The loss in global market share was driven by several factors:

- weaker growth of domestic demand in Europe (Europe's industrial output grew around 3% annually vs. ~5–6% globally),
- underperformance in export markets as European exports captured less of global growth than before, and
- lack of investment and competitiveness in the European domestic market over the past 15 years.

4. China's rapid expansion led it to jump from 19% to 43% of the global chemicals market and the United States benefited from cheap shale gas, and producers in the Middle East and India also expanded their chemicals output.

These trends have reshaped the global chemical industry, with Europe now a distant third in market share behind Asia and North America.
In recent crises, Europe's domestic chemical demand has been sluggish and even contracted. Between 2018 and 2023, Europe's chemical sector was hit by trade tensions, COVID-19 disruptions,

[98] Eurostat data 2023. Available at https://www.eureporter.co/health/2025/01/10/production-and-consumption-of-chemicals-dropped-in-2023/
[99] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Chemicals_production_and_consumption_statistics

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and an energy price shock, resulting in a sharper downturn than in other regions. European chemical production volumes fell by around 14% in 2022–2023 compared to 2021 levels amid weak demand and high energy costs. Meanwhile, import penetration in the EU chemical market has increased: imports supplied ~20% of Europe's chemical consumption in 2008, around 26% in 2018, and about 30% in 2023.

6.1.2 Employment, Gross value added: current status

According to CEFIC, in 2023 the chemical industry in the EU directly employs around **1.2 million people in a network of around 31,000 companies of which 97% SMEs**[82]. The sector supports an estimated **3.6 million of indirect jobs across the supply chains** reinforcing its importance for European social welfare. The sector generated around **€165 billion in gross value added (GVA)** in 2023, reflecting moderate growth despite recent macroeconomic headwinds. Productivity levels remain among the highest across EU manufacturing, owing to the industry's capital-intensive structure, advanced infrastructure, and strong innovation base. The presence of **over 150 chemical parks** across the EU further enhances regional industrial ecosystems, acting as employment hubs and centres of technical knowledge and cost-efficiency

6.1.3 Trade flows, tariffs and global competition

According to Eurostat [100], in 2023 EU was the largest exporter of chemical products with a total trade of of €848 billion, which consisted of €523 billions of exports and €325 billions of imports recording the highest trade surplus (€198 billion) as reported in Figure 5

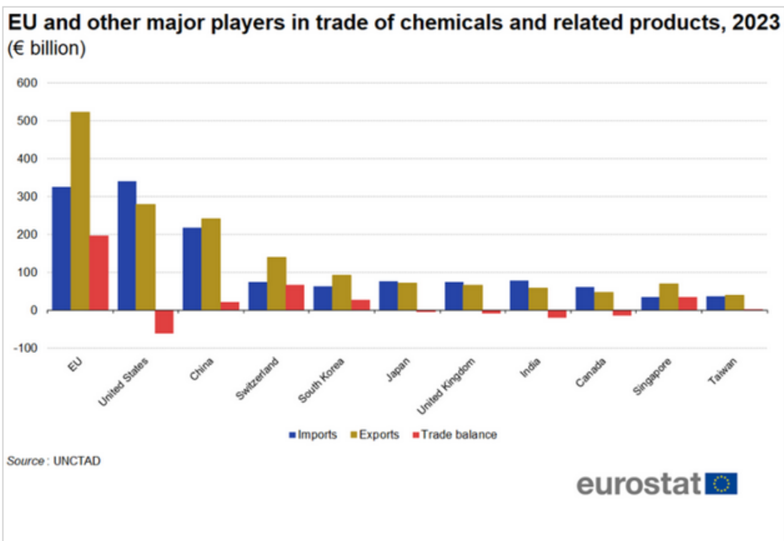

Figure 7. EU and other major players in trade of chemicals and related products. Source Eurostat 2023.

[100] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Trade_and_production_of_chemicals_and_related_products#EU_is_the_largest_exporter_of_chemical_products

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Key trade partners include the U.S., China, and the UK. However, EU producers face increasing competition from lower-cost jurisdictions with more lenient regulatory frameworks. Global competition is intensifying, particularly in basic chemicals and fertilisers, where China and the Middle East are increasing their capacity.

Europe's export performance also slipped – Europe's share of global chemical exports (excluding intra-EU trade) fell from ~7% in 2008 to ~5% in 2023. In short, European chemical producers have lost ground both in the domestic and international markets, ceding market share to foreign producers in its domestic market and capturing a smaller portion of growth overseas.

6.1.4 Overcapacity and plant closures

The European chemical industry is experiencing an unprecedented wave of site closures, largely driven by long-term overcapacity, high energy costs, and mounting global competition. Over 11 million tonnes of production capacity have already been announced for closure in 2023–2024, a level ten times higher than the annual variation observed over the past decade. Figure 8 presents the map of Europe with all the announced closures of chemical plants. **These closures span the entire chemical value chain, with organic aromatics representing the largest share (41%), followed by olefins (High Value Chemicals) (26%) and polymers (23%)[82].** The implications are significant: **the closure of 21 major sites puts between 10,000 and 20,000 direct jobs at risk, threatens 5 to 10 chemical parks, and could result in the loss of up to €2.5 billion in added value[82].**

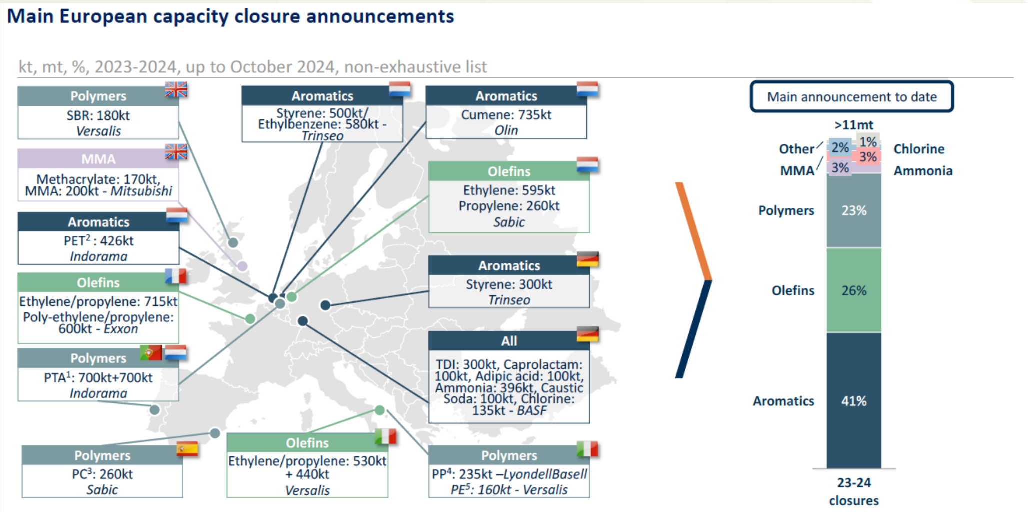

Figure 8. Main European capacity closure announcements. Source CEFIC 2025

Critically, once a chemical site shuts down, it is unlikely to reopen, due to the substantial capital required for restart and, in some cases, opposition from local stakeholders. The cumulative effect of these closures' risks reinforcing structural vulnerabilities and destabilising Europe's industrial clusters. Compounding this trend, the sector's capacity utilisation rates in Europe have fallen sharply by 5 to 10 percentage points since 2022, undermining profitability across upstream and polymer production.

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6.1.5 Cost Drivers

A key reason for Europe's competitiveness challenge is its unfavourable cost structure, especially for energy and feedstocks. Although energy prices have moderated from the peaks of 2021–2022, European producers still face much higher energy costs than many international competitors. While down from crisis levels, natural gas prices in Europe are projected to remain 2–3× higher than in the United States in the medium term, and electricity about 1.5–2× higher. Oil-based feedstock costs have also diverged: for crude-oil-derived naphtha, China and India gained a cost advantage (on the order of a 5–10% discount) by sourcing cheap Russian oil in recent years. This means European chemical plants reliant on naphtha pay more for feedstock than some competitors. Furthermore, Europe faces higher costs for certain raw materials due to policy factors, for example, bio-based inputs like bioethanol, sugar, and starch are pricier in Europe, influenced by local subsidies and differing tariff duties that raise input costs. In contrast, countries like China shield strategic inputs (e.g., ammonia, as seen in 2022) through export restrictions and price controls to keep their domestic costs low.

Labour costs in the European chemical industry are significantly higher than in Asia. On average, Europe's chemical labour cost is about double that of China or India, and around five times higher than in lower-cost Asian countries. (It is roughly 60% of US levels, as European labour is 6 times .6× cheaper than in the US). High labour costs and recent stagnation in productivity have weakened Europe's competitiveness. Over 2008–2023, European chemical labour productivity was flat and even declined slightly [ref], while China sharply improved productivity, closing the gap with Europe. Other regions like the US, South Korea, and Japan also show higher productivity than Europe. This means European producers get less output per worker per euro of wages than some key competitors, compounding the labour cost disadvantage (though cross-country productivity data must be interpreted cautiously).

Another cost driver is the **regulatory and compliance burden in Europe.** The industry faces rising costs to meet strict environmental and safety regulations, which, add to operating expenses. The CEFIC study notes that European chemical companies are affected by increasing environmental and regulatory costs compared to other regions. Complex approval processes and compliance requirements consume time and resources. In a survey in Germany, 60% of companies cited EU regulations as burden, and over half of SMEs identified regulation as the main obstacle to growth (ref). Regulatory costs and Europe's tax policies are part of the competitive equation. Unlike the US or China, which bolster industry with incentives (e.g. tax cuts or production subsidies), Europe's policy approach has tended to impose costs rather than offset them. This leaves European producers at a cost disadvantage not only in energy and labour but also in policy-driven costs (carbon costs, compliance, taxes) that their rivals may not bear to the same extent.

Despite these challenges, Europe remains a major player in the global chemical trade. The EU chemical industry historically runs a trade surplus, exporting more chemicals than it imports. In 2023, Europe's chemical trade surplus was about €35 billion (Ref), making chemicals the fourth-largest positive contributor to the EU manufacturing trade balance. Only machinery/transport equipment, pharmaceuticals, and food products ranked higher in trade surplus. This surplus reflects the strength of Europe's chemical producers, especially in higher-value segments like pharmaceuticals. However, the surplus has shrunk in recent years – Europe's chemical trade

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balance was traditionally even higher the sector was the 2nd or 3rd largest surplus generator, but higher energy costs in 2022–2023 increased import prices and eroded the EU's advantage in net trade of chemicals. The result was a smaller trade surplus than before, contributing less to Europe's overall manufacturing trade balance.

Not all parts of the chemical value chain perform equally in trade. The downstream segments, such as consumer chemicals and specialties, are strongly competitive globally, generating large export surpluses, whereas the upstream basic chemicals segment runs a deficit. In fact, Europe has been a net importer of basic organic and inorganic chemicals (upstream inputs) since around 2011 (ref). Europe shows a dependence on imported raw materials and basic feedstocks due to the energy and feedstock intensive nature of upstream production. On the other hand, downstream products, for example specialty chemicals and pharma intermediates, are key products for Europe's innovation that influence exports to other countries.

Europe faces minimal tariff barriers in many key markets under World Trade Organisation (WTO) rules, and chemical products generally has low tariff rates globally.

Import tariffs can strongly affect competitiveness: for example, import duties on bio-based feedstocks (like ethanol) contribute to higher raw material costs in Europe. In contrast, some competitor countries use export restrictions or tariffs strategically (China, for instance, restricts exports of certain fertilisers/ammonia to keep domestic prices low). Overall, trade policy factors (tariffs, trade agreements) are not identified as major current drivers of competitiveness in the report, aside from the new EU Carbon Border Adjustment Mechanism (CBAM), which aims to address carbon cost disparities. While intended to prevent carbon leakage, CBAM has shortcomings (e.g., it may impact export competitiveness and is administratively complex). Currently tariffs offer little protection for European chemical producers from global competition. The Europe's chemical industry remains focused on exports and active in the global market, but it faces increasing pressure due to higher energy costs and flattening domestic demand. The next sections will present technology, innovation, and other important factors influencing its competitiveness trajectory in Europe.

6.2 Technological Routes and decarbonisation

6.2.1 Main Technological routes in Europe

The Chemical industry includes a wide variety of processes and production processes but most of its emissions and energy use are concentrated in the production of few basic and primary chemical including ammonia, methanol, High Value Chemicals (HVCs), in particular ethylene and propylene. Table 7 provides a general framework of the sector in terms of raw materials and inputs, phases of production and outputs and applications. These upstream products serve as foundational inputs for polymers, agrochemicals, and industrial applications across the EU economy

Table 7. Overview of the Chemical Industry Value Chain: inputs, processes and outputs

Phase	Description
Raw materials	**Petrochemicals**: derived from natural gas and crude oil, petrochemicals include ammonia, methanol, ethylene, propylene, and benzene produced

and Inputs	by natural gas and other fuel fossils feedstock, which serve as building blocks for fertilisers, plastics, synthetic Fibers and resins. **Minerals and Inorganics**: Materials such as sulphur, chlorine and phosphates are extracted for fertilisers, chlorine production and other applications. **Biomass**: For certain specialty chemicals, renewable resources like plant-based oils or agricultural products may be used. **Air and Water**: Nitrogen from air and hydrogen from water are essential in the production of ammonia, a key component of fertilisers.
Chemical Production Processes	**Synthesis and Reactions**: this is the core of chemical processing, where raw materials undergo chemical reactions to form new compounds. This process can involve organic synthesis (carbon-based compounds) or inorganic synthesis (such as ammonia or sulfuric acid). **Separation Processes**: Techniques like distillation, crystallisation and extraction separate desired products from by-products. For example, crude oil is fractionated into various components in refineries. **Formulation**: Here, different chemicals are combined in precise ratios to create formulated products such as paints, adhesives, or cosmetics. **Catalysis and Polymerisation**: Catalysts speed up reactions without being consumed, essential for making products like polyethylene and other polymers. **Specialised Processes**: Chemical production also includes methods like fermentation (for biochemicals) or high-pressure reactions (for synthetic fuels and polymers).
Outputs and Applications	**Basic Chemicals**: Includes bulk chemicals like ethylene, sulfuric acid and methanol, used as precursors for more complex products. **Polymers and Plastics**: key outputs include plastics such as polyethylene, polystyrene and polypropylene which are ubiquitous in manufacturing, packaging, and consumer goods. **Fertilisers and Agrochemicals**: Products such as ammonia and urea are produced for agricultural use. **Specialty Chemicals**: Includes adhesives, sealants and cleaning agents which serve niche applications. **Consumer Chemicals**: Household products for cleaning or cosmetics and pharmaceuticals, come from this segment of the industry.

Steam cracking is the primary route for producing ethylene and propylene in Europe,

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relying predominantly on *naphtha* as feedstock with an average age of 45 years. Among the basic organic chemicals, ethylene and propylene are the largest in volumes of production. The map of steam cracker in Europe is presented in Figure 9 retrieved from CEFIC analysis.

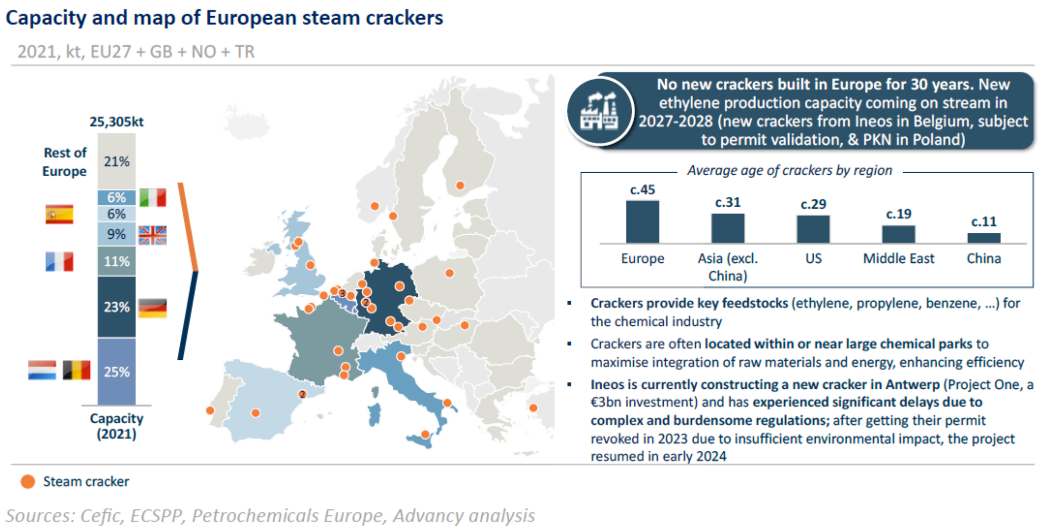

Figure 9. Capacity and map of European steam crackers (2021). Source CEFIC, ECSPP, Petrochemicals Europe

This contrasts with the **United States and the Middle East**, where cheaper ethane from shale gas gives producers a strong cost advantage. The EU's cracker fleet is relatively old with no new large-scale unit had been built for three decades until INEOS launched its "Project One" in Antwerp[82]. New capacity from INEOS (Belgium) and PKN Orlen (Poland), planned for 2027–28, may slightly improve competitiveness, though Europe's high energy costs and complex regulation remain barriers to large-scale rejuvenation[82]. The Middle East, with abundant oil and gas, also has advantaged feedstock for both naphtha and ethane-based crackers. Europe's reliance on higher-cost naphtha and the absence of similarly cheap gas feedstock means European crackers often sit higher on the cost curve.

Ammonia production Aside from petrochemicals, Europe's chemical industry has other key technological routes: ammonia synthesis (part of basic inorganics) primarily uses natural gas as feedstock and fuel. Ammonia is crucial for fertilisers and is energy intensive. In 2022–23, Europe's ammonia producers were severely impacted by record gas prices The result was a wave of permanent plant closures, with over **1.5 Mtons lost** particularly in sites in **Belgium, Germany, Spain, France, and the UK.** Closures include top producers such as YARA, BASFS and CF Ferilizers[101,102]. By contrast, in China, ammonia prices remained lower, thanks to government interventions (import/export restrictions and price controls to keep this fertiliser input affordable). This created a competitive gap, as Chinese producers did not face the same cost surge. The ammonia case underscores how technological route and energy source interplay affects

[101] https://www.spglobal.com/commodity-insights/en/news-research/latest-news/chemicals/122923-no-recovery-in-sight-in-2024-for-europes-crisis-ridden-chemical-industry
[102] https://www.linkedin.com/posts/matt-hoisch-943372109_breaking-yara-international-has-halted-ammonia-activity-7293677152351211521-eShw

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competitiveness: European ammonia (made via Haber-Bosch process using gas) was temporarily uncompetitive when gas spiked, highlighting a vulnerability in Europe's current route for this chemical. It also highlights a strategic opportunity: ammonia is emerging as a key piece in decarbonisation.

Another critical route for Europe, according to CEFIC the is **chlor-alkali electrolysis**, where electricity is used to convert salt into chlorine, caustic soda, and hydrogen. While most mercury-based cells have been phased out in favour of membrane technology, electricity prices in Europe remain 2–3 times higher than in competing regions, directly impacting the competitiveness of this segment. Moreover, because chlorine is hazardous and costly to transport, its production tends to be locally anchored to downstream demand, reinforcing the need for industrial integration.

6.2.2 Decarbonisation options for Chemicals

According to IEA, reducing emissions in the chemical sector demands a multi-pronged strategy, with particular emphasis on technologies capable of addressing both feedstock-related and process-related emissions. Two of the most promising pathways are the deployment of carbon capture, utilisation and storage (CCUS) and the adoption of low-carbon hydrogen, particularly green hydrogen produced via electrolysis using renewable electricity. Moreover, as a significant share of chemical process heat, estimated at roughly 30% according to IEA, is required at relatively low temperatures (below 200 °C), electrification technologies such as high-temperature heat pumps offer attractive efficiency gains and the potential for integration with clean electricity systems.

The cross-cutting strategies applicable to both petrochemicals and chemicals are briefly outlined below, along with key decarbonisation routes for selected basic petrochemicals—in particular ammonia and high-value chemicals (HVCs). This overview is not intended to be exhaustive, given the broad scope of the topic and the focus of this deliverable.

Low-Carbon Hydrogen for Ammonia and Methanol production

The main chemical routes for producing ammonia and methanol includes the use of hydrogen as main feedstock produced mainly from fossil fuel and in particular natural gas (see Section 7 on hydrogen for more detail). Ammonia is currently produced from natural gas with hydrogen produced via steam reforming (grey ammonia), and it can be decarbonised, producing green hydrogen from electrolytic production coupled with renewable electricity production. Ammonia is also a key component of the decarbonisation pathway for Europe came the most important because it can be hydrogen carrier and a carbon-free fuel. The development of renewable ammonia (from water electrolysis hydrogen,) These new routes could enable fertiliser production with far lower CO_2 emissions. A notable example of innovation in clean ammonia production is emerging in Denmark, where the world's first industrial-scale, renewables-based power-to-ammonia plant designed for dynamic operation is expected to begin activity in 2024. The facility is being jointly developed by Skovgaard Energy, Topsoe, Vestas and ABB. Its key feature lies in its ability to respond directly to fluctuations in renewable electricity supply, operating only when sufficient power from wind or solar is available, without relying on intermediate energy storage. This flexibility marks a crucial step in aligning ammonia synthesis with variable renewable generation.

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Also, one of the key basic chemicals, methanol can be decarbonised trough low-carbon hydrogen.[103] More broadly, hydrogen can replace carbon-intensive feedstocks in synthetic chemistry and provide high-temperature heat.

Carbon Capture, Utilisation and Storage (CCUS)

For processes that inherently produce CO_2 (such as hydrogen from methane, ammonia from gas, or cement and lime in allied industries), carbon capture offers a way to reduce emissions without completely changing the production route. Blue ammonia is one such approach in chemicals: capturing the CO_2 from conventional ammonia plants and storing it to achieve a lower carbon product. CCUS could also be applied in olefin production (e.g. capturing CO_2 from furnace flue gas) or in refining and hydrogen production that supply chemical sites. Europe is investing in CCUS hubs (e.g. North Sea storage projects) which could benefit clusters of chemical plants.

Bio-based and Circular Feedstocks

Another decarbonisation route is to shift from fossil feedstocks to bio-renewable or recycled inputs. Biomass-based chemicals (bio-ethanol, bio-naphtha, or bio-waste) can reduce lifecycle emissions, mainly if sustainably sourced. Similarly, using biomass or waste gases to produce methanol or other platform chemicals is being explored in Europe. In addition, the industry is moving toward a circular economy model: developing chemical recycling processes to convert plastic waste back into feedstock (naphtha or monomers) and using mass balance approaches to integrate recycled content. Chemical recycling (like pyrolysis of waste plastics) and increased recycling of solvents, CO_2 utilisation for chemicals, etc., can all lower the virgin fossil input and associated emissions. Lyondell Basell is currently building a demo plant in Wesseling (Germany)[104].

Electrification of processes

Replacing fossil fuel heat with electric energy (ideally from renewable energy sources) can drastically cut CO_2 emissions in high-temperature chemical processes. For example, research is underway into electric steam crackers using electric heaters instead of gas-fired furnaces to produce ethylene. The Green Deal explicitly encourages "decarbonisation of the chemical industry: electrification and new processes. Electrification could also apply to chemical reactors, distillation (using heat pumps), and other unit operations, reducing direct combustion emissions. A transition to low-carbon electricity is a prerequisite for this route.

Process innovation and efficiency

Beyond significant shifts in feedstock or energy, many incremental technologies can decarbonise chemical production. This includes developing low-energy process routes (novel catalysts, membrane separations instead of energy-intensive distillation, etc.), improving heat integration, and increasing efficiency. Deployment of digital process controls (discussed in the next section) can also optimise energy use. The EU's policies (e.g., RED II directive, energy efficiency targets)

[103] https://www.iea.org/reports/chemicals

[104] https://www.lyondellbasell.com/en/news-events/corporate--financial-news/lyb-lays-foundation-for-1st-industrial-scale-advanced-recycling-plant-at-wesseling-germany-site/

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push for such improvements. Additionally, some emerging processes (e.g. direct electrochemical synthesis of chemicals, enzymatic routes at low temperatures) could in the long term replace older high-heat processes, though these are mostly at R&D stage.

In summary, Europe's chemical industry is at a technological inflection point. Current production routes face cost and carbon challenges, but the industry has options to innovate.

Decarbonisation of ammonia

Focusing on ammonia production, several decarbonisation pathways are available, reflecting the full spectrum of low-carbon options. These include:

- **Green ammonia** (also referred to as RNFBO – Renewable Fuels of Non-Biological Origin), produced using **renewable hydrogen** from water electrolysis;
- **Blue ammonia**, based on **natural gas reforming** with **CO_2 capture and storage (CCS)**;
- **Bio-ammonia**, produced using **hydrogen from biomass-based feedstocks**.

All these alternatives contrast with conventional **grey ammonia**, which relies on the Haber-Bosch process using unabated methane as feedstock.

It is worth noting that, even in conventional production, **60–70% of CO_2 emissions are already captured for urea synthesis**. However, net emissions remain significant. Decarbonised routes can reduce emissions considerably, with estimated values ranging from:

- **0.3 to 1.0 tonnes of CO_2 per tonne of NH_3** for blue ammonia,
- **0.1 to 0.8 tonnes** for bio-ammonia,
- **below 0.1 tonne** for green ammonia, depending on the electricity mix and system boundaries considered as reported in Figure 10.

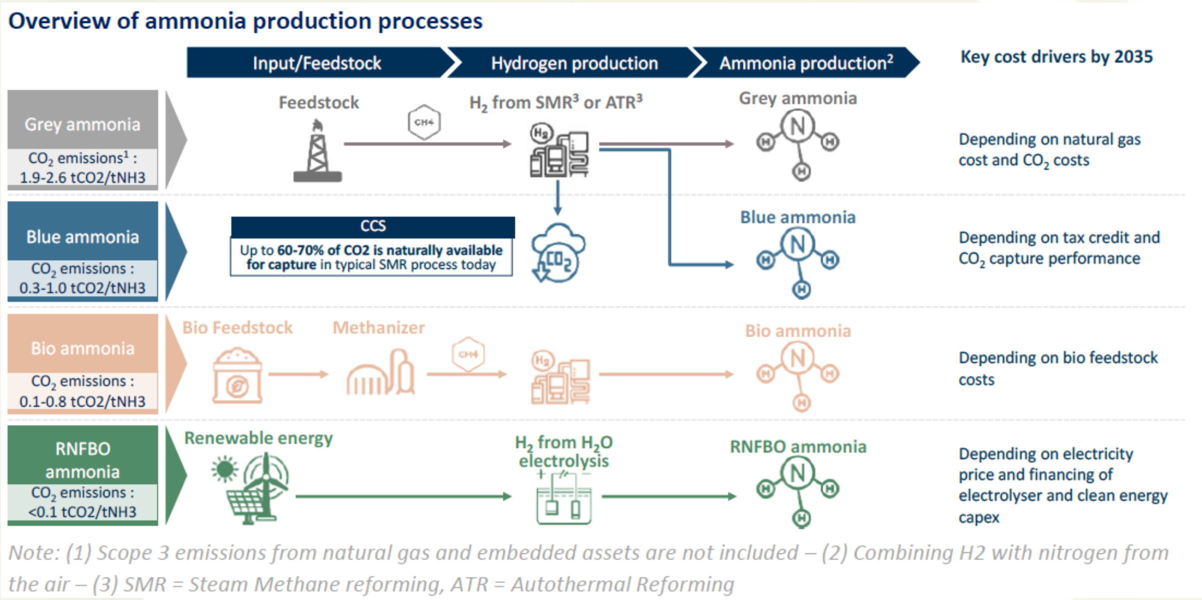

Figure 10. Overview of ammonia production processes and main decarbonisation routes including blue ammonia with CCS, bio ammonia and renewable ammonia.

Decarbonisation of HVCs in Europe

High-value chemicals, such as ethylene, propylene and aromatics (BTX)—form the backbone of Europe's chemical industry, serving as critical building blocks for plastics, solvents, and synthetic fibres. Currently, these are predominantly produced through naphtha-based steam cracking, a highly fossil- and energy-intensive process. The decarbonisation of HVC production is therefore essential, but it must be approached pragmatically, given the scale of existing infrastructure and global competition.

Several technological pathways are being explored to reduce the carbon footprint of HVCs production in Europe. The authors of this deliverable analysed the most promising routes with a focus on EU starting from **IEA ETP Clean Technology Guide**[105]

- **Steam cracker electrification** is one of the most promising options. By replacing fossil fuel-based furnaces with electric heating, this route can significantly cut emissions if powered by renewable electricity. Initiatives such as the Cracker of the Future consortium (including BASF, SABIC, LyondellBasell, and TotalEnergies), as well as pilot plants by Dow–Shell and Coolbrook, are already testing this approach. While still at **TRL 5, it is considered a strategic long-term route for the EU, aligned with climate neutrality targets.**
- **Chemical recycling and pyrolysis of plastic** waste offer a complementary pathway by feeding recycled pyrolysis oil into existing crackers. This route supports EU circular economy goals and is being piloted by companies such as LyondellBasell and Neste, though regulatory clarity and scale-up remain key challenges.
- **Bio-based routes, such as the production of bio-ethylene via ethanol dehydration,** are commercially mature but face feedstock limitations in Europe. Most of the capacity exists in Brazil and India, and the availability of sustainable biomass within the EU is constrained.
- **Methanol-based routes (e.g., methanol-to-olefins and methanol-to-aromatics)** are emerging as potential alternatives, especially if green methanol becomes available at scale. However, these processes are methanol-intensive and currently more prominent in China, where pilot and early commercial plants are being developed.

Table 8 provides a comparative overview of the most relevant options, highlighting their current development status and strategic value for the EU chemical sector.

Table 8. Comparative assessment of selected decarbonisation routes for high-value chemicals. Source: own elaboration based on IEA Clean Energy Technology Guide (2024) and Cefic–Advancy (2024)

Route Technology	Feedstock	Main Products	TRL (2024)	Decarbonisation Potential	EU Relevance Feasibility	Details
Naphtha catalytic cracking (FCC)	Naphtha (fossil)	Propylene, olefins	9	Low	Short-term efficiency gain	Mature, fossil-based route; optimises existing assets
Synthetic H_2-based fuels in crackers	Synfuels (H_2 + CO_2)	Ethylene, propylene	7	High	Theoretical fit; constrained by green H_2 cost	Very energy-intensive, only niche pilots

105 https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide

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Electric steam cracking	Naphtha, bio-naphtha	Ethylene, propylene	5	Very High	Strategic route for EU net-zero	Pilots underway (Dow-Shell, Coolbrook, BASF-SABIC); needs infra
Pyrolysis of plastic waste	Plastic waste	Pyrolysis oil, monomers	6–7	Medium–High	Strong policy alignment	Supports circular economy; regulatory clarity and scale-up ongoing
Bio-ethylene via ethanol fermentation	Bioethanol	Ethylene	9	Medium–High	Limited sustainable biomass in EU	Commercial outside EU (e.g. Brazil); biomass availability a constraint
Methanol-to-Aromatics (MTA)	Low-carbon methanol	BTX (benzene, toluene, xylenes)	7	Medium–High	High methanol input requirement	Chinese leadership; limited pull in EU unless methanol is green

Finally, incremental innovations like naphtha catalytic cracking (FCC-based) or synthetic hydrogen-derived fuels for crackers can improve efficiency or diversify inputs, but they do not offer deep decarbonisation unless coupled with renewable feedstocks.

In conclusion, steam cracker electrification and chemical recycling currently represent the most promising options for large-scale, EU-compatible decarbonisation of HVC production, while bio-based and methanol routes may serve niche or transitional roles depending on feedstock availability and infrastructure readiness.

6.3 Key Competitiveness Factors for the Chemical Industry in EU

According to CEFIC analysis, in assessing the European chemical industry's competitiveness, it is helpful to summarise the key factors into two broad categories: Price/Cost Competitiveness Factors and Non-Price Competitiveness Factors. Price factors determine the cost at which European producers can make and deliver products. In contrast, non-price factors determine the industry's ability to differentiate, innovate, and operate effectively beyond just cost. Below is a summary of the main factors.

6.3.1 Price and Cost Competitiveness Factors

Energy and Feedstock Costs

Energy remains the single largest cost component for many chemical production processes, and it represents a key structural disadvantage for Europe. According to Cefic, natural gas prices in Europe have been two to three times higher than in the United States in recent years, while electricity prices are 1.5 to 2 times higher. These price gaps directly impact the cost-competitiveness of energy-intensive processes such as ammonia synthesis, methanol production, and steam cracking for high-value chemicals.

In addition to energy, feedstock costs are also higher in Europe. Oil-derived inputs such as naphtha, used extensively in steam crackers, are significantly more expensive than in regions like Asia, where countries such as China and India benefit from discounted crude imports and integrated petrochemical-refining systems. Moreover, European producers often face higher raw material costs due to tariff structures, limited domestic availability, and lower subsidy levels compared to competitors.

These combined factors exert upward pressure on operating costs and weaken Europe's price positioning in global chemical markets. Addressing this cost gap will require both structural reforms, such as investments in lower-cost, low-carbon energy and a strategic shift toward alternative feedstocks, including renewable electricity, hydrogen, and circular raw materials ad discussed in Sections 2 and 7.

Labour Costs

Labour costs in the European chemical industry are significantly higher than in Asia, amounting to approximately twice the level in China and up to five times higher than in some emerging economies. Although European labour costs remain below those in the United States (1.6 less according to CEFIC), they are still a major cost item, particularly in segments where human capital intensity is high and process automation is limited.

Crucially, this cost premium has not been accompanied by commensurate gains in productivity. While Europe continues to benefit from a highly skilled workforce, recent data suggest that labour productivity in the EU chemical sector has stagnated, whereas countries like China have achieved rapid improvements in output per worker. As a result, Europe is increasingly paying more for labour without corresponding efficiency gains, which gradually erodes its global competitiveness. To address this, the sector must focus on raising productivity through automation, digitalisation, and targeted workforce upskilling. Leveraging Europe's deep expertise in chemical engineering and its dense industrial clusters, especially through integration of Industry 4.0 tools, can help justify higher wages and restore a balanced cost–performance ratio.

In summary, while labour costs represent a moderate disadvantage for Europe, this is partly offset by skill intensity and operational reliability. Closing the productivity gap will be essential to sustaining competitiveness in a high-cost labour environment.

Capital Costs and Investment Challenges

Europe’s chemical industry is increasingly constrained by capital-related disadvantages. While the nominal *cost of capital* may not be the highest globally, access to capital and the willingness to invest in Europe have become serious concerns compared to the US and Asia. According to Cefic, Europe’s *share of global chemical investment* has dropped from 18% in 2008 to just 12% in 2023, while China’s share has surged from 29% to 46% over the same period. **A critical issue is the *aging capital stock*: many of Europe’s production assets are over 45 years old, with few world-scale plants having been built in recent decades. Investments are often driven by compliance and maintenance needs rather than capacity expansion or innovation. This results in lower productivity and reduced competitiveness over time.**

Furthermore, *high regulatory costs* divert a substantial share of capital expenditure—up to 10% according to the study—leaving less room for growth-focused investment. Declining revenues in 2023–2024, combined with fixed cost pressures, have further reduced investment capacity, especially in the scale-up of new technologies.

To remain competitive, Europe must facilitate access to finance for industrial innovation and decarbonisation. This includes improving policy predictability, reducing permitting delays, and de-risking large-scale investments.

Environmental and Regulatory Costs

Europe's regulatory framework, while designed to uphold high standards for environmental protection, health and safety, imposes significant direct and indirect costs on chemical producers. Companies must invest heavily in compliance systems, emissions abatement technologies, and administrative resources to manage a complex and evolving set of obligations. These burdens are substantially higher than in other global regions, where regulatory systems are often more streamlined or focused on incentivising investment.

A prominent example is the EU Emissions Trading System (ETS), under which European chemical producers pay for carbon emissions. While carbon pricing is a necessary tool to drive decarbonisation, it also contributes to elevated operating costs in the short term, especially when not matched by equivalent policies abroad. As of 2023–2024, no comparable cost burden exists for producers in the United States, China, or the Middle East, widening the competitive gap.

Beyond direct compliance costs, the administrative complexity of EU regulations—requiring dedicated personnel, external consultants, and lengthy permitting processes—adds to the financial and operational pressure. According to Cefic, regulatory costs absorb up to 10% of total capital investment in some cases, limiting the ability of firms to allocate resources to innovation or capacity expansion.

Unless addressed through compensatory mechanisms (e.g. Innovation Fund support, faster permitting, carbon border adjustments) or regulatory simplification, these "self-imposed" costs will continue to undermine Europe's industrial competitiveness. The challenge lies in balancing the legitimate societal goals of regulation with the economic viability of the chemical sector—a balance that remains fragile in the current policy environment.

Subsidies and Taxes

This factor refers to government fiscal policies that can either alleviate or exacerbate cost Fiscal policy, through subsidies, tax regimes, and public support mechanisms, plays a critical role in shaping industrial competitiveness. In this respect, Europe has historically lagged behind global peers. According to Cefic, European chemical producers receive relatively limited subsidies compared to counterparts in the United States, China, or the Middle East. In these regions, governments frequently provide direct or indirect support such as subsidised energy and feedstocks, preferential land use, tax credits for investment, or streamlined fiscal regimes for industrial projects.

By contrast, European policy has traditionally focused more on regulatory compliance than on financial incentives. High energy taxation and stricter fiscal frameworks contribute to elevated production costs. Moreover, public support for innovation and decarbonisation—through mechanisms like the Innovation Fund or IPCEIs—has only recently begun to scale up. Until now, European firms have largely borne the full cost of deploying new technologies, placing them at a disadvantage when competing globally. To rebalance this, the EU is advancing initiatives such as the Green Deal Industrial Plan, state aid reform, and emerging clean tech investment platforms. These efforts aim to close the incentive gap and ensure that the transition to climate neutrality does not come at the expense of industrial competitiveness.

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Infrastructure Costs

The efficiency and cost of transporting raw materials and products is another price factor. Europe's internal logistics infrastructure is quite advanced, which gives a competitive advantage – transport within Europe can be cost-effective thanks to good roads, rail, waterways, and integrated chemical clusters. In global terms, Europe invests heavily in infrastructure, more so than the US in recent years (with programs like NGEU). This means getting goods to port or to customers might be cheaper or faster out of Europe than from some competitor nations, which is a strength. However, as noted, the lack of a fully unified transport market and variability across countries can introduce inefficiencies.

Additionally, external factors like global freight costs impact all exporters – recent supply chain crises drove up shipping costs temporarily, highlighting vulnerabilities. Overall, logistics costs are one area where Europe is not a significant disadvantage and, in some aspects, an advantage. However, there is room to streamline and improve cross-border operations to reduce costs further. Maintaining robust infrastructure investment is key to preserving this edge.

6.3.2 Non-Price Competitiveness Factors: innovation and digitalisation, cluster ecosystem and policy environment.

Innovation and Digitalisation Capability

Innovation remains one of Europe's most important competitive advantages in the chemical industry. European companies rank among the global leaders in R&D investment and patent activity, particularly in high-value segments such as sustainable materials, specialty chemicals, and pharmaceuticals. According to Cefic, **European firms invest around 1.6% of their sales in R&D, slightly behind the 2.1% reported in the United States but well above levels in China and other emerging economies.** In absolute terms, R&D spending in Europe's chemical sector amounts to **€10–12 billion annually**. When measured against **value-added**, Europe leads globally, with around **6% of value-added reinvested in R&D**, compared to **5% in the US**, demonstrating the sector's strategic commitment to innovation beyond raw output.

These investments translate into a strong pipeline of intellectual property. **In 2022, approximately 6,000 chemical patents were granted by the European Patent Office to applicants based in Europe.** European innovators also rank second in chemical patents granted in the United States and in Patent Cooperation Treaty (PCT) applications globally. This reflects the capacity of Europe's chemical ecosystem including spanning firms, research institutions, and universities, to generate new processes, formulations, and materials that support differentiation and quality, not just cost.

Yet Europe's lead cannot be taken for granted. Countries like China are rapidly scaling up R&D efforts and patent output in areas such as biotechnology, green chemistry, and advanced materials, investing heavily in education and innovation capacity. The United States has also boosted public funding for cleantech and industrial innovation. To maintain its edge, Europe must continue to support the full innovation chain from fundamental science to commercial deployment ensuring that new technologies can scale efficiently.

Digitalisation is also emerging as a strategic lever for competitiveness. While the adoption of digital technologies in the chemical sector is gradual, the potential impact is significant. Advanced data analytics, machine learning, digital twins, and IoT-enabled process control can improve efficiency, reduce energy use, accelerate R&D (e.g. through in silico modelling), and optimise supply chains. Recognising this, industry leaders and policy initiatives have identified digitalisation as a priority, calling for increased investment in digital infrastructure, skills, and regulatory support to "make the innovation framework smarter."

Underlying this innovation capacity is Europe's human capital. The chemical sector benefits from a highly educated workforce, a strong tradition in chemical engineering, and dense knowledge networks clustered around chemical parks, universities, and research institutes. These ecosystems support continuous skill development, applied research, and technical excellence. Operating complex integrated chemical plants safely and efficiently requires decades of accumulated know-how, something Europe has cultivated and must preserve. While other regions are catching up in terms of investment and talent, Europe's combination of scientific expertise, engineering capacity, and innovation infrastructure remains a key differentiator. Maintaining this edge will require sustained efforts in STEM education, vocational training, and support for early-stage innovation.

Supply and Demand Ecosystem (Cluster and Value Chain Integration)

The European chemical industry benefits from a critical mass and integration of its value chain. Europe's chemical clusters (e.g. in Antwerp, Rotterdam, the Rhine-Ruhr, etc.) create dense networks of suppliers, producers, and customers in proximity. This ecosystem provides security of supply and efficient utilisation of by-products, for example, one plant's output (or waste heat) can provide inputs to another plant, improving overall competitiveness. The integrity of the long value chain is stronger when many chemical subsectors are present within the region. Europe produces everything from basic petrochemicals to specialties and pharmaceuticals, which means downstream users can source materials locally and collaborate on innovation. Europe has a robust chemical manufacturing ecosystem as a non-price strength. It also contributes to resilience; however, this ecosystem has shown some vulnerability recently with site closures (if parts of the chain shut down, it can ripple through). Maintaining a full value chain and sufficient critical mass is important that once lost, it is hard to rebuild (a closed cracker means dependent units may also fail). Europe still has one of the largest chemical industries in the world by output, so its ecosystem is generally intact. Another aspect is the **security of supply**: having domestic production of key materials (or multiple suppliers globally) so that European industries downstream are not reliant on imports that could be disrupted. Europe's ecosystem traditionally gave it self-sufficiency in many chemicals, but with **rising import shares, this security is weakening in some base chemicals.** The recommended actions include reinforcing raw material security (e.g. via recycling and partnerships).

Policy and Regulatory Environment

The policy framework is a defining factor for the competitiveness of the European chemical industry. Compared to other major regions, the EU is widely perceived by stakeholders as offering a **less favourable regulatory environment**, where policy priorities have largely focused on **environmental protection and safety**, often without sufficient attention to cost competitiveness. According to the Cefic–Advancy study, EU regulation is "mainly focused on restrictions rather than incentives," and does not guarantee favourable operating conditions—particularly in terms of **energy prices, tax burden, or administrative complexity**.

This imbalance translates into a **heavy regulatory load**. Companies must comply with numerous

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overlapping policies, including REACH, climate and industrial emissions directives, and product-specific safety rules, all of which entail significant administrative and compliance costs. In response to these concerns, the European Commission announced in February 2025 that, as part of the *Clean Industrial Deal*, the upcoming *Chemicals Industry Package* will include a **major revision of REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals)**. This revision expected by the end of 2025[106] and expected to be the most extensive since REACH was introduced, aims to streamline registration, enhance enforcement, enable digitalisation, and modernise risk management processes. The revision also promises to improve transparency and accelerate the identification and restriction of hazardous substances, potentially reshaping the sector's compliance landscape.

While the EU tightens regulatory requirements, other global regions have taken a more proactive approach to industrial policy in the last years. The United States, for instance, has introduced powerful incentive frameworks such as the Inflation Reduction Act (IRA), offering significant subsidies, tax credits, and direct support to clean technology deployment. China, meanwhile, pursues a state-driven industrial strategy that includes coordinated investments through state-owned enterprises, long-term subsidies, and clear goals for strategic self-sufficiency in chemicals and materials.

In this global context, European producers face a growing competitive disadvantage. Stakeholders across the industry are calling for a reset of EU industrial policy. Initiatives like the Antwerp Declaration and the forthcoming Draghi Report call for decisive action to reverse industrial decline: simplifying the regulatory landscape, increasing financial support for green technology deployment, reducing administrative burdens, and ensuring policy coherence and predictability.

Predictability is a recurring concern. Companies require long-term clarity on carbon pricing, future regulatory restrictions, and the availability of investment incentives. Ongoing uncertainty, such as questions around CBAM effectiveness, future bans on specific chemicals, or evolving sustainability criteria, risks delaying or diverting investment outside Europe.

Finally, fiscal measures also influence competitiveness. Europe's relatively high energy taxation and limited direct industrial subsidies contribute to an uneven playing field. Competitor regions often offer tax breaks, low-cost energy, or subsidised land to attract chemical investments. In response, European industry stakeholders are advocating for initiatives such as a Clean Tech Deployment Fund to mirror U.S. financial instruments, and for embedding competitiveness as a central filter in EU policymaking. This includes systematically assessing whether new legislative proposals risk undermining industrial capacity or innovation and adjusting them accordingly.

[106] https://www.ricardo.com/en/news-and-insights/industry-insights/proposed-changes-to-eu-reach-chemical-regulation

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7 Clean energy technology industries

Following the analysis of energy-intensive industrial sectors facing steep decarbonisation challenges, in this section the focus is on the sector that underpins their transformation, clean energy technologies.

The clean-tech sector is both a critical enabler of climate neutrality and a strategic industry key, for Europe's affordable and resilient pathway towards net-zero. It encompasses a diverse set of technologies and value chains, including renewable energy systems, electrolysers for green hydrogen, batteries and energy storage, heat pumps, advanced biofuels, and carbon capture. These are building blocks of a low-carbon industrial system, essential not only to reduce emissions, but to maintain competitiveness in a rapidly changing global landscape.

Positioned at the intersection of innovation, industrial policy, and sustainability, the clean-tech sector plays a dual role. First, it provides the technologies that hard-to-abate sectors need to decarbonise and second it represents a new frontier of economic and employment opportunities with potentially large potential for exports and job creation. The sector however also faces growing pressures, global competition for supply chains and manufacturing capacity, rising demand for critical raw materials, and the need to rapidly scale up production while maintaining environmental and social standards. The race is not just to deploy clean tech, but to produce it in EU, ensuring strategic autonomy and resilience.

In 2023, clean energy technologies contributed around USD 320 billion to the global economy, about 10% of global GDP growth[107]. Considering investments in clean energy manufacturing (solar PV, wind, and battery value chains), deployment of clean power capacity (including solar PV, wind, nuclear, battery storage, and electricity networks), and sales of clean equipment (EVs and heat pumps), the share of clean energy technologies in GDP for the United States, China, the European Union, and India is shown in Figure 11. China is a clear front runner in clean energy investments, followed by the EU, and dominates in clean energy manufacturing. Deployment of power technologies is more evenly distributed among regions, reflecting a shared commitment to decarbonisation. China and the EU stand out for their substantial investments in electrification and demand-side transformations, followed by the US, while in contrast, India's focus remains more limited in these areas.

[107] IEA (2024), Clean energy is boosting economic growth, IEA, Paris https://www.iea.org/commentaries/clean-energy-is-boosting-economic-growth

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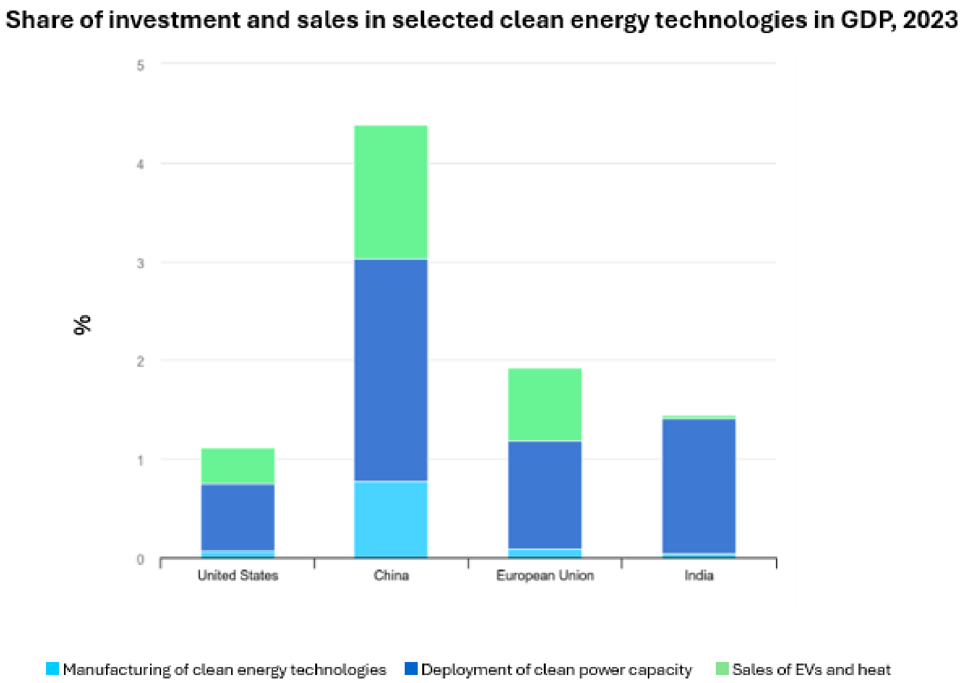

Figure 11. Share of investment and sales in selected clean energy technologies in GDP, 2023[108]

In 2023, global renewable capacity additions surged by over 60% to nearly 565 GW, the fastest annual growth on record (Figure 12). This was driven by strong policies in over 130 countries and falling solar PV costs. China led this expansion, contributing two-thirds of global additions. Solar PV and wind are the leading technologies with a share of over 95% of overall capacity additions.

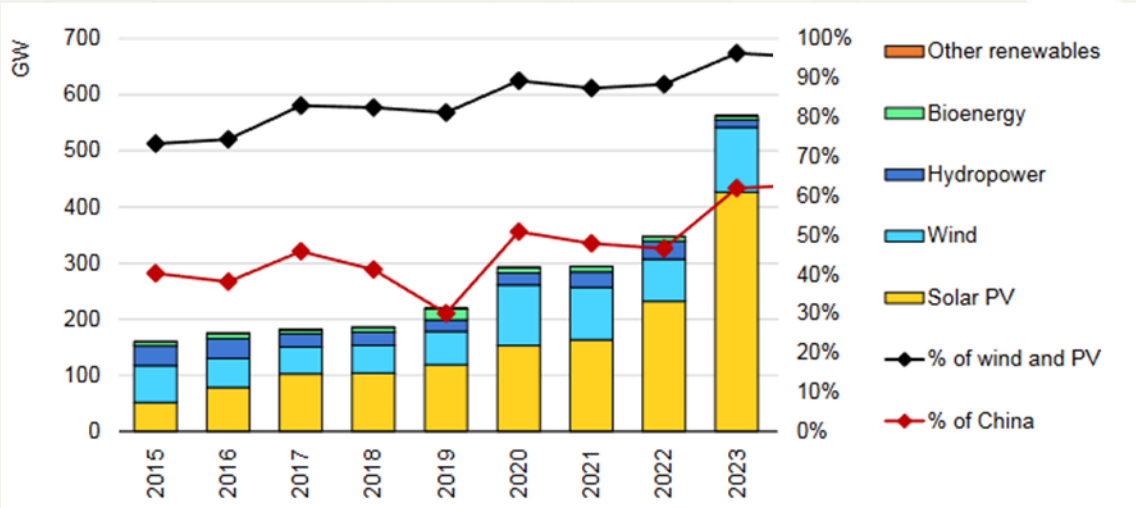

Figure 12. Renewable electricity capacity additions by technology (2015-2023)[109]

The global market for net-zero technologies is set to nearly triple by 2035, reaching EUR 1.9 trillion

[108] IEA (2024), Share of investment and sales in selected clean energy technologies in GDP, 2023, IEA, Paris https://www.iea.org/data-and-statistics/charts/share-of-investment-and-sales-in-selected-clean-energy-technologies-in-gdp-2023
[109] https://iea.blob.core.windows.net/assets/17033b62-07a5-4144-8dd0-651cdb6caa24/Renewables2024.pdf

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annually[110]. In this rapidly growing market, the EU must ensure its competitiveness to meet the demand for clean energy technologies, both within Europe and globally. However, challenges such as high interest rates, inflation, access to critical raw materials, high energy and labour costs, and geopolitical uncertainties complicate long-term investments in manufacturing facilities. Delays in building net-zero manufacturing capacities could harm the EU's future competitiveness in clean tech and other industries and hamper EU's security.

Countries worldwide, including the US, China, and others, are introducing industrial policies to support clean energy technology manufacturing. The US, through the Inflation Reduction Act, has allocated EUR 461 billion to support the manufacturing of clean energy technologies, with 60% aimed at the energy sector[110]. China remains a dominant player in the clean tech production, especially in solar PV and battery manufacturing, where it controls over 90% of global production. These trends underscore the need for the EU to accelerate efforts to build resilient supply chains and cost-efficient manufacturing capacities to remain competitive in the clean tech sector.

7.1 Overview of the EU clean technology sector

The European Union is at a pivotal moment in its transition to a low-carbon and digitally integrated economy. The twin transition is at the core of the EU's industrial strategy, positioning clean technology manufacturing as a fundamental driver of economic growth, competitiveness, and strategic autonomy. As global markets for clean energy technologies rapidly expand, the EU aims to secure its leadership in key sectors while reducing reliance on imported critical raw materials.

The EU has set ambitious climate and energy targets, aiming to become the first climate-neutral continent by 2050 under the European Green Deal. In 2023, the European Union ranked as the world's second-largest installer of most clean technologies, following China (IEA, World Energy Outlook 2024[111]). The implementation of the net-zero goal requires a massive scale-up of renewable energy, electrification, low and zero-carbon technologies (including green hydrogen and carbon capture), and energy efficiency measures, which in turn demands a robust and resilient clean technology manufacturing sector. The Net Zero Industry Act (NZIA) and the Green Deal Industrial Plan reflect the EU's push to strengthen domestic clean tech production while reducing EU's import dependence on major carbon tech suppliers, particularly China. Strategic autonomy is a central objective of these policies. The COVID-19 pandemic and geopolitical tensions, particularly Russian's invasion in Ukraine but also the recent imposition of import tariffs by the US, have underscored the vulnerabilities of global supply chains of clean technologies. These events highlighted the need for Europe to reduce dependencies on foreign suppliers, especially for technologies that are critical for the energy transition (solar panels, wind turbines, batteries, etc).

Clean tech manufacturing plays a key role in this shift, providing the physical infrastructure necessary to decarbonise energy, transport and industry. The REPowerEU plan, aimed at reducing fossil fuel imports and accelerating clean energy deployment, further reinforces the need for a

[110] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52025DC0074
[111] https://iea.blob.core.windows.net/assets/140a0470-5b90-4922-a0e9-838b3ac6918c/WorldEnergyOutlook2024.pdf

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strong European clean tech industry. However, scaling up clean technology production requires significant investments in research development and industrial capacity. The EU's existing manufacturing base is strong in certain areas such as wind power and electric vehicle components, but remains highly dependent on imports in others, particularly solar PV and battery manufacturing. The challenge lies in bridging these gaps while maintaining competitiveness against countries with lower production costs, easier access to raw materials, and more extensive government subsidies.

Since 2020, the EC publishes annual progress reports on the competitiveness of clean energy technologies and their manufacturers in EU. The 2025 report focuses on the 15 most important clean technologies listed in Table 9, which mostly coincide with the net-zero technologies within the scope of NZIA.

Table 9. Clean energy technologies included in the annual progress reports on competitiveness

Number	Clean Technology
1	**Solar photovoltaics**
2	**Solar thermal**
3	**Onshore and offshore wind energy**
4	**Ocean energy**
5	**Battery and energy storage**
6	**Heat pump technologies**
7	**Geothermal energy**
8	**Hydrogen technologies: electrolysers and fuel cells**
9	**Sustainable biogas and biomethane technologies**
10	**Carbon capture and storage (CCS) technologies**
11	**Electricity grid technologies: power lines and transformers**
12	**Nuclear fission energy technologies**
13	**Hydropower**
14	**Sustainable alternative fuels**
15	**Industrial excess heat recovery technologies**

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According to the Clean Energy Technology Observatory (CETO), the EU production value in clean technologies was highest for batteries with a production value of 21 billion euros, followed by biodiesel, bioenergy, and wind power. The European production value of CCUS and fuel cells are quite limited as these technologies are in early commercialisation phase as seen in Figure 13[112].

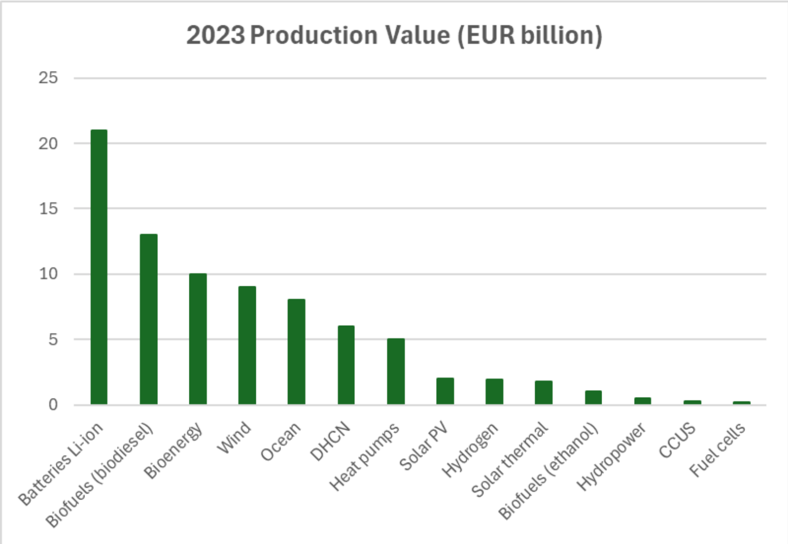

Figure 13. EU production value of clean technologies in 2023 (source: CETO reports)

In the same year, the EU had a negative trade balance in eight out of the twelve clean energy technologies of the CETO report, with the largest deficits, each approaching 19 billion euros, occurring in solar PV and Li-ion batteries (Figure 14). In 2023, wind technology led the surplus with EUR 1.7 billion, marked by a 65% drop in imports and a 50% increase in exports compared to the previous year. Heating and cooling networks followed with a surplus of EUR 1.3 billion, while hydropower had EUR 0.2 billion. Hydrogen and CCUS had smaller surpluses, at EUR 7 million and EUR 4 million, respectively. EU trade surplus in hydrogen more than tripled, with imports falling by 70% and exports rising by 40%.

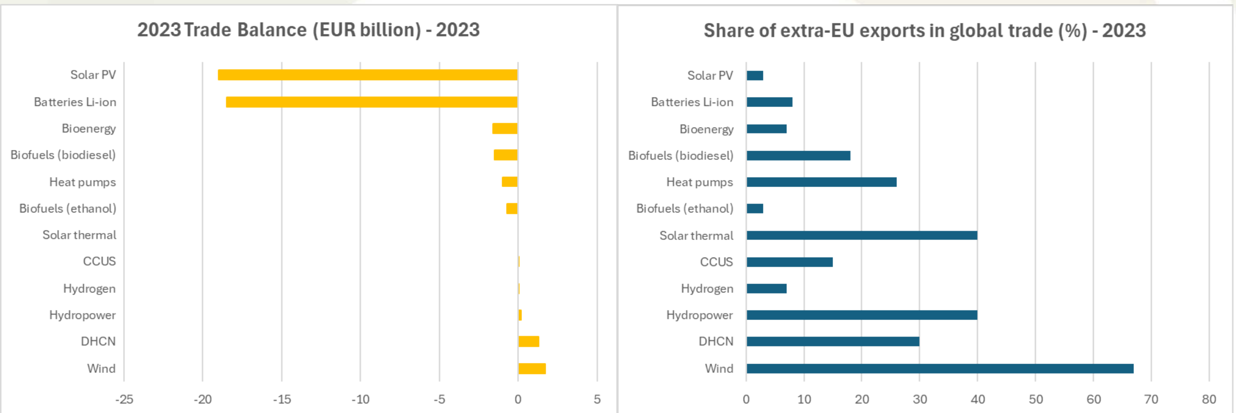

Figure 14. Clean technologies EU trade balance and share of extra-EU exports in global trade (source: CETO reports)

112 https://setis.ec.europa.eu/publications-and-documents/clean-energy-technology-observatory/ceto-reports-2024_en

The cost structures of clean technologies such as batteries, solar PV, wind turbines, CCS, and heat pumps share several similarities with those of traditional energy-intensive industries (EIIs) like cement, steel, and chemicals, but also differ in important ways. Raw material costs are significant in both, though clean technologies often rely on critical minerals (e.g., lithium, cobalt, rare earths) (Section 7.3), whereas EIIs depend on bulk commodities like limestone, iron ore, or hydrocarbons. Energy costs are also substantial across the board, operational energy use is particularly high in EIIs due to thermal processes, while in clean technology manufacturing, energy is heavily embedded in upstream processing (e.g., mining, refining, or high-temperature manufacturing). Capital intensity is high in both domains, but while EIIs involve large, long-lived infrastructure like kilns and blast furnaces, clean technologies often require precision manufacturing equipment and rapidly evolving production lines.

Labour costs tend to be relatively low to moderate in both sectors due to increasing automation, although clean tech manufacturing (especially for batteries and heat pumps) can involve more skilled labour. Overall, both sectors are capital- and material-intensive, but clean energy technologies face distinct cost pressures due to reliance on scarce raw materials and evolving manufacturing processes.

Employment in the renewable energy sector

In 2023, global employment in the renewable energy sector in total reached 16,2 million jobs. China led this sector with an estimated 7,4 million jobs, accounting for 46% of the global total. The European Union followed with 1,8 million jobs, while the United States had 1,1 million jobs. Figure 15 highlights China's dominant position in renewable energy employment, reflecting substantial investments and rapid expansion in the sector. For the EU to enhance its leadership in clean technology manufacturing, addressing this employment disparity is crucial.

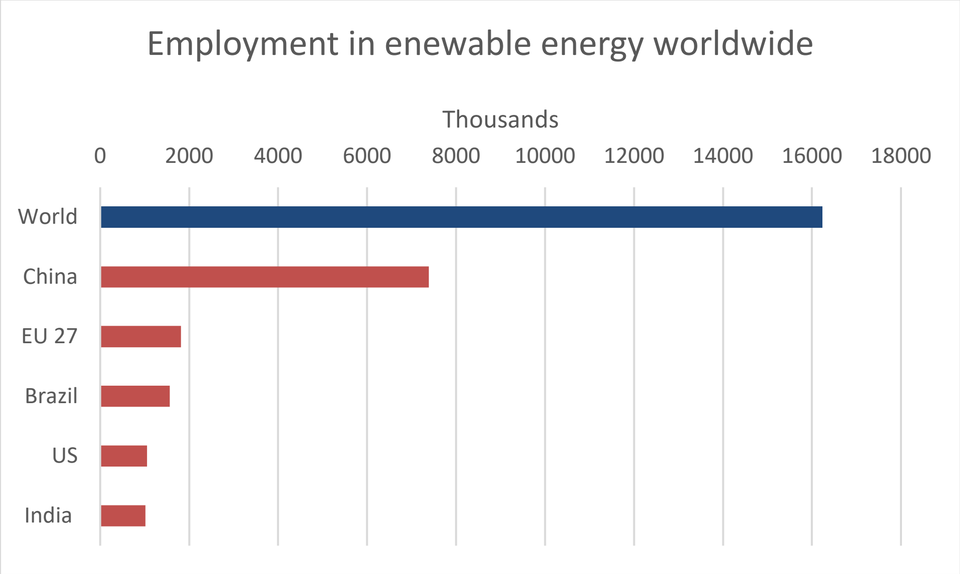

Figure 15. RES jobs in 2023[113]

7.2 Clean energy technologies

7.2.1 Solar

Solar photovoltaic (PV) technology generates electricity by converting sunlight directly into electricity using semiconductor materials, typically silicon. It is one of the most scalable and widely deployed renewable energy technologies and the global PV sector in 2023 had a total business value of USD 400 billion[114] and employed approximately 7 million people[115]. Global solar PV capacity tripled between 2018 and 2023, reaching approximately 1,642 GW in 2023[80]. In the same period, solar PV's share of global electricity generation rose from 2.1% in 2018 to 5.4% in 2023[116].

Photovoltaic (PV) energy, though intermittent due to its dependence on sunlight (solar irradiation) and low-capacity factor, is constantly maturing, improving, and diversifying in application. A key trend in 2023 is agrivoltaics, which integrates PV with agriculture for dual land use. PV is increasingly combined with other clean technologies, such as battery storage for improved dispatchability and green hydrogen production, to enhance grid stability and support the decarbonisation of energy-intensive industries.

7.2.1.1 Global demand for solar PV

The global annual installed PV capacity is depicted in Figure 16[117]. The annual growth rate in 2023 reached nearly 75%, driven mainly by China (235 GW), in an effort to absorb the unprecedented

[113] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Oct/IRENA_Renewable_energy_and_jobs_2024.pdf
[114] https://iea-pvps.org/wp-content/uploads/2024/10/IEA-PVPS-Task-1-Trends-Report-2024.pdf
[115] https://www.statista.com/statistics/1498261/global-employment-in-solar-photovoltaics/
[116] https://www.iea.org/energy-system/renewables/solar-pv
[117] https://iea-pvps.org/wp-content/uploads/2024/04/Snapshot-of-Global-PV-Markets-1.pdf

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oversupply[118], with a global market share of 58%, followed by EU with a share of 14% (55.8 GW), and the US with a share of 7% (30 GW).

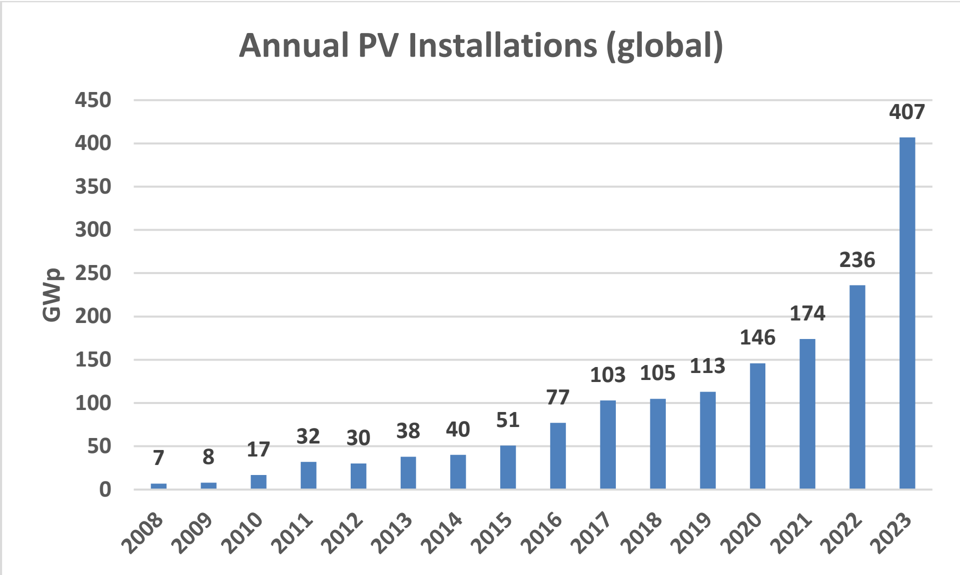

Figure 16. Global annual PV installations (2008-2023) – China's lower bound considered for 2023

7.2.1.2 Solar PV Value Chain

The solar PV value chain, without considering project development, installation, grid connection, and maintenance services spans several stages: production of raw materials (such as polysilicon), manufacturing of wafers, solar cells, and modules, as well as the assembly and integration of components like inverters, mounting systems, and other balance of system (BoS) equipment. The breakdown of utility-scale solar PV total installed costs in 2023 is shown in Table 10.

Table 10. Breakdown of utility-scale solar PV total installed costs in 2023[119]

	Share of total cost (Range)
Modules & Inverters	32%-52%
BoS* hardware components	17%-39%
Installation costs	9%-26%

Total installed costs for utility scale PV installations have a continuously downward trend in the

[118] https://sinovoltaics.com/solar-market/global-solar-pv-module-market-trends-navigating-oversupply-regulations-and-quality-control-challenges/#:~:text=Oversupply%20remains%20a%20central%20theme,and%20further%20consolidation%20seems%20inevitable.

[119] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf

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period 2010 to 2023, despite a sudden rise of PV modules in 2021[120],with the global weighted average dropping from 5310 USD(2023)/kW in 2010 to 758 USD(2023)/kW in 2023 (Figure 17), largely driven by cost reductions in PV module prices driven by rapid innovation dynamics and learning by doing/economies of scale in manufacturing activities.

Global weighted average total installed costs of utility-scale solar PV systems and cost reductions by source [2010-2023]

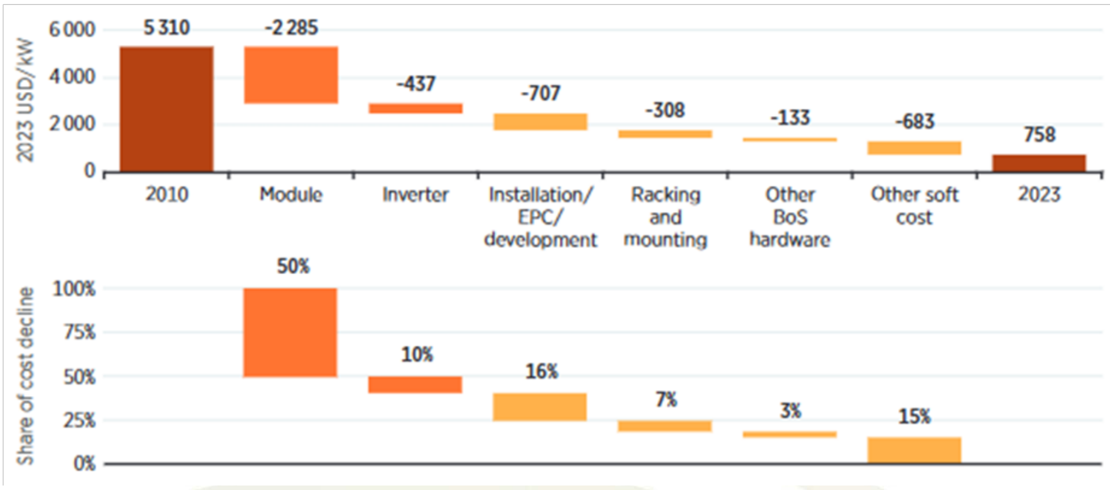

Figure 17. Global weighted average total installed costs of utility-scale solar PV systems and cost reductions by source, period 2010-2023

The overall cost reductions in the utility scale installations of solar PV, have steadily reduced the Levelised Cost of Electricity (LCOE) of solar PV[121], as shown in Figure 18.

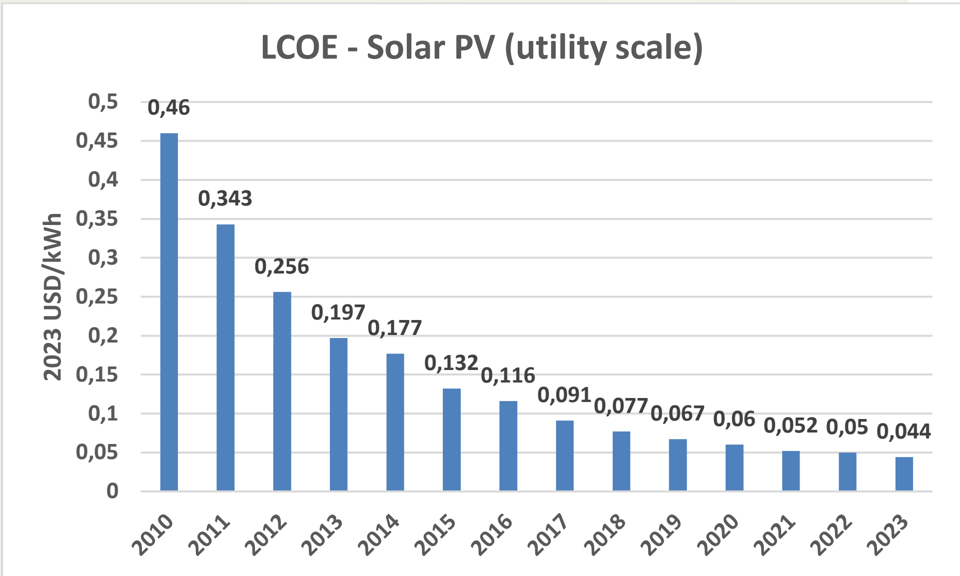

Figure 18. Global LCOE average of solar PV installations (utility-scale)

[120] Solar PV module prices rose in 2021 due to supply chain issues (mainly polysilicon) but began falling again in 2022, reaching their lowest level since 2017 by early 2024

[121] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf

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7.2.1.3 Solar PV manufacturing capacity

Over the past decade, global solar PV manufacturing capacity has steadily shifted from Europe, Japan, and the United States to China[122]. In 2023, China dominated the global PV solar manufacturing across key manufacturing stages[123]. China's control over the production of these critical components (polysilicon, wafers, cells, modules) is substantial, with the country accounting for over 98% of global wafer production and poses a significant vulnerability for the global supply chain.

Table 11. Share of production by country across solar PV components (2023)[124]

	Polysilicon*	Wafer	Cell	Module
China	92.0%	98.0%	91.8%	84.6%
Germany	4.0%	-	-	-
USA	2.0%	-	0.8%	2.2%
Malaysia	2.0%	-	2.3%	2.1%
Vietnam	-	2.0%	1.7%	3.4%
South Korea	-	-	1.6%	-
Chinese Taipei	-	-	0.6%	-
Thailand	-	-	0.6%	2.3%
India	-	-	0.5%	2.7%
Other	-	1.0%	0.1%	2.6%

**Production of semiconductors is included*

Europe accounted for 21% of global solar inverter production capacity in 2023, while most capacity remains concentrated in Asia, especially China[125]. Although Chinese firms dominate their domestic market, European manufacturers hold a stronger presence in the PV markets of Europe and the Americas.

The EU holds a small share of the global solar PV manufacturing capacity and remains reliant on imports from China, particularly for the components needed to assemble solar panels. In 2023, China emerged as the dominant supplier, accounting for 98% of the EU's extra-imports of solar panels[126]. In monetary terms, the EU imported €19,7 billion worth of solar panels from China[125]. The global solar PV market is experiencing a manufacturing oversupply, with production capacity outpacing demand. This surplus, driven largely by rapid capacity expansion in China, has led to falling prices but also raises concerns about market volatility and the long-term viability of manufacturers outside China and poses a challenge for EU who needs strengthen its own

[122] https://www.iea.org/reports/solar-pv-global-supply-chains/executive-summary
[123] https://iea-pvps.org/wp-content/uploads/2024/10/IEA-PVPS-Task-1-Trends-Report-2024.pdf
[124] https://iea-pvps.org/wp-content/uploads/2024/10/IEA-PVPS-Task-1-Trends-Report-2024.pdf
[125] https://api.solarpowereurope.org/uploads/SPE_Inverters_Explained_2_0_2024_V01_656a82d39e.pdf?updated_at=2024-06-19T14:17:45.349Z
[126] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=International_trade_in_products_related_to_green_energy

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manufacturing capacity to reduce dependence on China and ensure energy security.

7.2.2 Wind

Wind energy harnesses kinetic energy from the wind to generate electricity via wind turbines, typically deployed onshore and offshore. It is a mature and rapidly expanding renewable energy source, valued for its high energy return on investment and its scalability from distributed to utility-scale projects. In 2023, the global wind energy market had a total value of USD 87.7 billion[127] and supported around 1.4 million jobs worldwide[128]. The year 2023 marked the most significant growth in wind energy installations to date, with an additional capacity of 117 GW[129] and the total global wind power capacity surpassed the 1 TW milestone setting new global records. The amount of wind generated electricity in the same year was 216 TWh and held a share of 7.8% in the global electricity mix[125].

Wind energy, while variable and location-dependent, is becoming increasingly flexible and hybridised. A key trend in 2023 is the development of floating offshore wind, which enables deployment in deeper waters and expands geographic potential. Additionally, wind is increasingly integrated with energy storage systems, green hydrogen electrolysers, and digital forecasting tools to enhance system stability and reduce curtailment. Innovations in turbine design, digital twin technology, and repowering strategies are also extending turbine lifetimes and increasing capacity factors, helping to decarbonise sectors like transport and heavy industry.

7.2.2.1 Global demand in wind technology

The global cumulative installed wind capacity for onshore and offshore wind installations is depicted in Figure 19[130]. The annual growth of total global installed wind capacity has been relatively steady in the period 2015-2023 (range 9%-17%) with an average growth rate of 12%. Since 2015, China has led the world in cumulative onshore wind capacity, previously led by the EU, reaching 403 GW (43%) of installed capacity in 2023, followed by the EU with 201 GW (21%) and the US with 150 GW (16%). China became the global leader in offshore wind capacity following major deployments in 2021, reaching 37.8 GW in 2023 (50%), followed by the EU with 19.2 GW (25%) and the UK with 14.8 GW (20%).

In 2023, China dominated the global wind market for both onshore (69.2 GW – 65% market share) and offshore wind (6.3 GW – 57% market share)[130]. The EU is the second largest market in both offshore and onshore wind with 13.3 GW (13%) new onshore installations and 2.9 GW (26%) capacity additions in offshore wind.

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[127] https://www.skyquestt.com/report/wind-energy-market
[128] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Oct/IRENA_Renewable_energy_and_jobs_2024.pdf
[129] https://www.iea.org/energy-system/renewables/wind
[130] https://publications.jrc.ec.europa.eu/repository/bitstream/JRC139320/JRC139320_01.pdf

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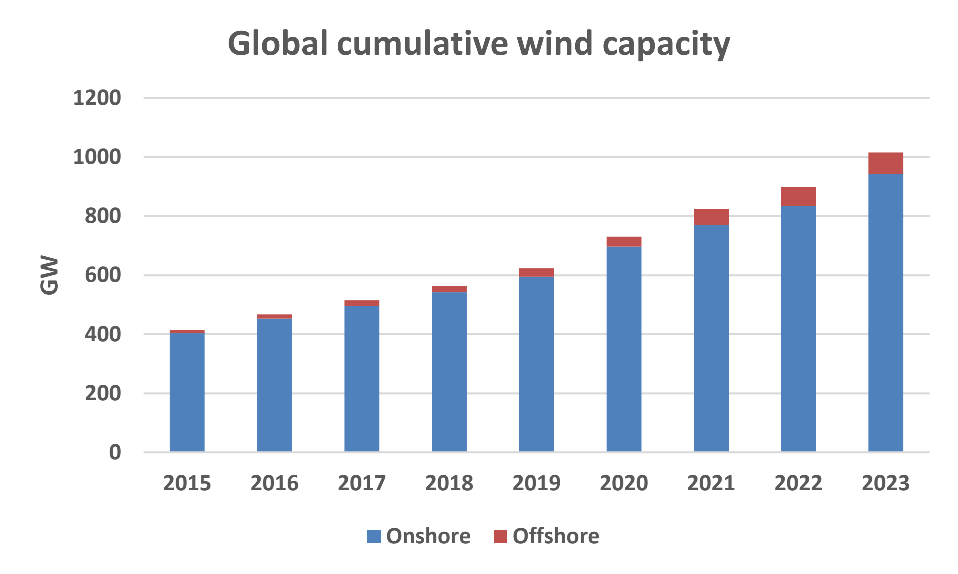

Figure 19. Global cumulative installed wind capacity (2015-2023)

7.2.2.2 Wind value chain

Wind energy production relies on a complex value chain that starts with sourcing essential raw materials like iron ore, copper, silica, copper, and aluminium, which are processed into steel, carbon fibre and fiberglass. These materials are transformed into the main components of a wind turbine: blades that capture wind energy; a nacelle, which houses the generator, gearbox, and control systems; a tower that elevates the turbine to reach stronger winds; and electrical systems that transmit power to the grid. Once manufactured, these components are assembled and delivered to installation sites, where project development tasks, including site preparation, permitting, and grid integration, take place.

The global weighted average total installed cost of both onshore and offshore wind projects has a declining trend in the period 2010-1023, driven by cost reductions in wind turbine prices and balance of plant costs[131] which has led to a decrease in LCOE of wind production (Figure 20)

[131] https://www.irena.org/Data/View-data-by-topic/Costs/Global-Trends

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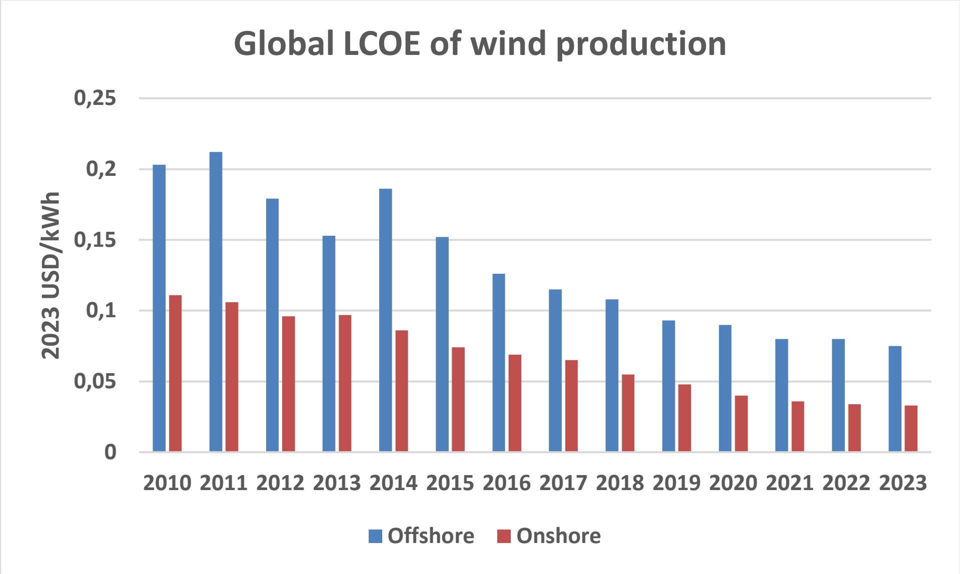

Figure 20. Global LCOE of wind production (offshore and onshore)

Wind turbines, however, remain the dominant cost component of wind installations worldwide in 2023 which represent between 64% and 84% of total installation costs for onshore projects[132]. This share drops for offshore projects to 30%-43%, as other costs, such as installation, foundations, and electrical interconnection, account for a significant portion of the total expenditure of offshore deployment.

7.2.2.3 Wind manufacturing capacity

The EU has long been at the forefront of the global wind industry, maintaining a strong position through technological innovation and a skilled industrial base. However, its competitiveness is now increasingly under pressure from China, which benefits from economies of scale, state support, and aggressive international expansion, particularly in turbine manufacturing and exports. The share of manufacturing capacity across regions for key components of wind turbines are shown in Table 12 for 2024[133]. In the same year, EU held 21.8% of the global tower manufacturing[134].

Table 12. Global share of manufacturing capacity of blades and nacelles

	Blades	Nacelles
China	60%	65%
EU	12%	15%

[132] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf
[133] https://publications.jrc.ec.europa.eu/repository/bitstream/JRC139320/JRC139320_01.pdf
[134] https://energy.ec.europa.eu/publications/2025-progress-report-competitiveness-clean-energy-technologies_en

Europe (non-EU)	5%	-
America	13%	9%
Asia (except China)	10%	10%

The EU's wind turbine manufacturing capacity in 2023 was roughly 150% to 185% of the region's annual installations (16.2 GW), with European manufacturers supplying the majority of turbines used within the EU market[135].

Table 13. Share of wind turbines manufacturers in the EU market

Manufacturer	Country	Onshore Share	Offshore Share
Vestas	Denmark	44%	44%
Siemens Gamesa	Germany / Spain	18%	56%
Nordex	Germany	22%	-
Other European	Various (EU)	4%	-
General Electric	United States	5%	-
Unknown	—	6%	-

Given the existing skill sets and infrastructure, EU manufacturers continue to export wind turbines to other economies that have not yet developed local competitive manufacturing capacity, however the global market in 2023 saw Chinese manufacturers holding a dominant 63% share of the onshore wind turbine sector. European manufacturers followed with 27% and American firms with 7%. In contrast, European companies led the global offshore market, capturing 58% of the total share, largely due to the prominence of Vestas and Siemens[100] (Table 14).

Table 14. Share of wind turbines manufacturers in the global market

Manufacturer	Country	Onshore Share	Offshore Share
Vestas	Denmark	13%	36%
Siemens Gamesa	Germany / Spain	7%	22%
Nordex	Germany	6%	-
Other European	Various (EU)	1%	-

[135] https://publications.jrc.ec.europa.eu/repository/bitstream/JRC139320/JRC139320_01.pdf

Goldwind	China	14%	-
Envision	China	12%	-
Windey	China	9%	-
SANY	China	7%	-
MingYang	China	6%	21%
Dongfang	China	5%	-
Other Chinese	China	10%	-
General Electric	United States	7%	-
Unknown	-	2%	-
Other	Various	1%	21%

Europe's wind industry, with decades of experience, strong policy support, and technological advancements, remains a key player in both onshore and offshore markets. However, EU companies face significant challenges, especially from China, where turbines are priced about 32% lower than European-made ones[136]. The EU's Wind Power Package and continued investments in supply chain expansion highlight its commitment to maintaining leadership in renewable energy manufacturing and achieving the REPowerEU target of 420 GW of wind capacity by 2030.

7.2.3 Batteries in the energy sector

Battery technologies store electricity in chemical form and are used across a wide range of applications, including Electric Vehicles (EVs), stationary energy storage systems (Battery Energy Storage Systems – BESS), and portable electronics. Consumer electronics, once the primary market for batteries, now account for only a small share of global battery demand ~2%[137]. Today, the energy sector[138] is the main driver of battery deployment (98% of global battery demand), with transport, particularly EVs, representing the dominant share ~90%[138] and the revenue of the global battery[139] market in 2023 was approximately 118 billion USD[140].

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[136] https://energy.ec.europa.eu/publications/2025-progress-report-competitiveness-clean-energy-technologies_en
[137] https://publications.jrc.ec.europa.eu/repository/bitstream/JRC139392/JRC139392_01.pdf
[138] Although lithium-ion batteries continue to power billions of personal devices worldwide, the energy sector now accounts for more than 90% of annual lithium-ion battery demand (IEA (2024), *Batteries and Secure Energy Transitions)*
[139] Battery market includes Lead Acid, Lithium Ion, Nickel-based, Sodium-ion, Flow Battery, Small Sealed Lead-acid Batteries
[140] https://www.grandviewresearch.com/horizon/outlook/battery-market-size/global#:~:text=The%20global%20battery%20market%20generated,USD%2050%2C853.9%20million%20in%202023.

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Battery use in the transport sector (EV)

Battery deployment in transport is primarily driven by the shift toward electric mobility. Lithium-ion batteries power a growing fleet of electric cars, vans, buses, and trucks, enabling decarbonisation and reducing reliance on fossil fuels. In addition to the primary use as an alternative "fuel", batteries are increasingly used for vehicle-to-grid (V2G) technologies, which allow EVs to discharge electricity back to the grid, supporting grid stability and demand management. By the end of 2023, there were 40 million EVs worldwide[141], making up 2.7% of the global light vehicle fleet of 1.5 billion, or 1.9% for Battery EVS (BEVs) alone[142]. On average, batteries represent 40% of an EV's total value[143]. Battery size ranges according to the type of EV, typically Plug-in Hybrid EVs (PHEVs) have smaller batteries than BEVs - the average usable battery capacity of different models of BEVs is 71.2 kWh[144].

Battery use in the power sector

In the power sector, batteries are increasingly deployed to enhance grid reliability and support the integration of renewable energy. By storing electricity during periods of low demand and releasing it when needed, Battery Energy Storage Systems (BESS) help balance supply and demand, defer grid infrastructure investments, and reduce curtailment of solar and wind energy. As V2G capabilities scale, the boundary between transport and stationary storage is blurring, offering new opportunities for distributed energy flexibility. In 2023, battery storage became the fastest-growing energy technology in the power sector, with deployments more than doubling compared to the previous year[145] and global installed capacity reached 89GW (189GWh)[146].

7.2.3.1 Global demand in EVs and BESS

The global annual sales of EVs by region[147] and the global annual additional capacity of BESS are shown in Figure 21. In 2023, EVs accounted for 18% of global car sales, with market shares of 38% in China (59% of total EV sales), 22% in the EU (6% of total EV sales), and 9.5% in the USA (10% of total EV sales) and these three regions in the same year represented 73% of the global EV fleet[148].

141 https://www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer
142 https://ev-volumes.com/news/ev/global-ev-sales-for-2023/
143 https://www.acea.auto/files/ACEA_Fact_sheet-EU_battery_supply_chain_and_import_reliance_.pdf
144 https://ev-database.org/cheatsheet/useable-battery-capacity-electric-car
145 https://www.iea.org/reports/batteries-and-secure-energy-transitions
146 https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf
147 https://www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer

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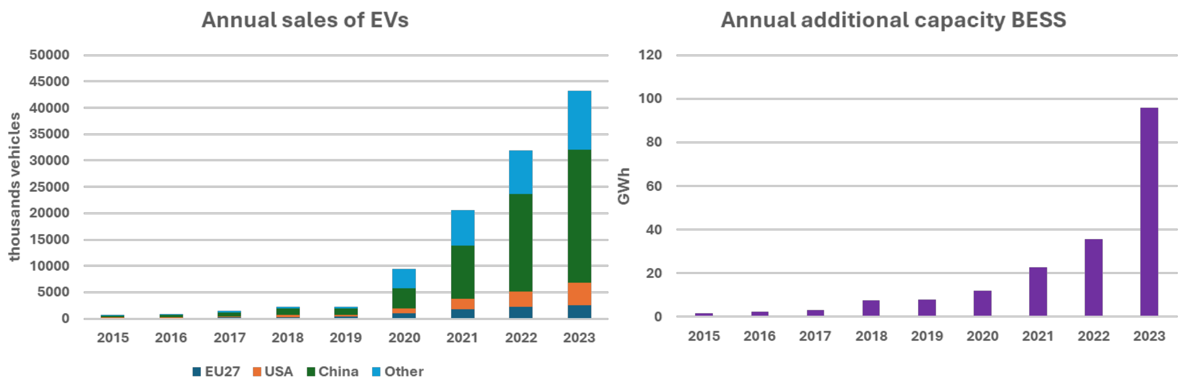

Figure 21. Annual sales of EVs (BEV, PHEV, FCEV) for cars, trucks, buses, vans by region and global annual additional capacity of BESS for the period 2015-2023

The global market for BESS has seen incremental growth in the last years and the new additions in 2023 reached 95.9 GWh[148], effectively doubling the available stationary battery storage capacity. China led global growth in 2023, adding 46.5 GWh of battery capacity, nearly half of all new installations worldwide, followed by the US with 22GWh[148] and the EU with 19.1 GWh[149]

7.2.3.2 Batteries value chain

Lithium-ion batteries have become the leading choice for both EVs and energy storage, thanks to significant cost reductions and performance gains over the past decade[150]. The lithium-ion battery value chain includes several stages: raw material extraction, refining and processing, component production (anodes, cathodes, electrolytes), cell manufacturing, battery pack assembly, integration into products (EVs, storage), and recycling and second life[150].

Over the past decade, lithium-ion battery prices have fallen significantly due to advances in research, larger production volumes, and technological improvements. The battery industry continues to invest in lithium iron phosphate (LFP), a low-cost cathode chemistry. In 2023, LFP packs and cells had the lowest global average prices among all lithium-ion batteries, dropping below key cost thresholds (USD 100/kWh)[150]. As costs declined, raw materials began to account for a larger portion of total expenses, increasing sensitivity to fluctuations in mineral prices, evident by the increase of price in 2022 due to increased demand of critical materials (Figure 22).

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[148] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf
[149] https://api.solarpowereurope.org/uploads/SPE_European_Battery_Outlook_2025_62b89db476.pdf
[150] https://iea.blob.core.windows.net/assets/cb39c1bf-d2b3-446d-8c35-aae6b1f3a4a0/BatteriesandSecureEnergyTransitions.pdf

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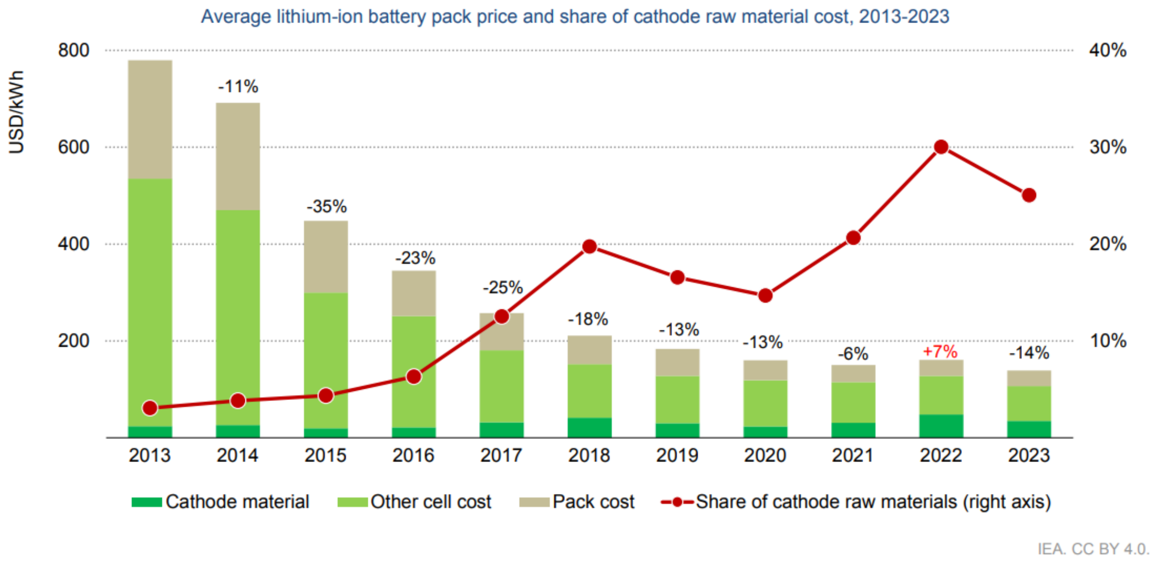

Notes: Cathode material costs include lithium, nickel, cobalt and manganese. Other cell costs include costs for anode, electrolytes, separator and other components as well as costs associated with labour, manufacturing and capital depreciation. Percentages on bars show year-on-year total pack price change. Analysis includes all cathode chemistries and global chemistry sales shares.
Source: IEA analysis based on BloombergNEF (2024).

Figure 22. Average lithium-ion battery pack price (LFP) and share of cathode raw material cost for the period 2013-2023[151]

EV batteries are designed for high energy and power density to maximise driving range and performance while keeping weight and size low. They must support fast charging, have strong thermal management, and be durable enough to handle varying road and climate conditions. In contrast, batteries used in the power sector prioritise long cycle life, safety, and cost-effectiveness over compactness, with a focus on delivering stable, sustained energy output for grid reliability rather than mobility. This is reflected in the choice of suitable technologies and in general the cost of BESSs is higher than those of EVs, with a global average of USD 290/kWh in 2022[150].

7.2.3.3 Battery manufacturing capacity

The geographical distribution of the global battery supply chain is depicted in Figure 23 for the year 2023[153]. China leads every stage of the downstream battery supply chain, processing over half of global lithium, cobalt, and graphite. It controls nearly all graphite anode production, produces the vast majority of cathode and anode active materials, and holds 85% of battery cell manufacturing capacity and leads the global batter production with an 83% share. The EU has very limited presence in the supply chain, with a share in cobalt mining and processing, mainly due to Finland (10%), and represents 7% of global battery production, while the US follows with 6%.

[151] https://iea.blob.core.windows.net/assets/ee01701d-1d5c-4ba8-9df6-abeeac9de99a/GlobalCriticalMineralsOutlook2024.pdf

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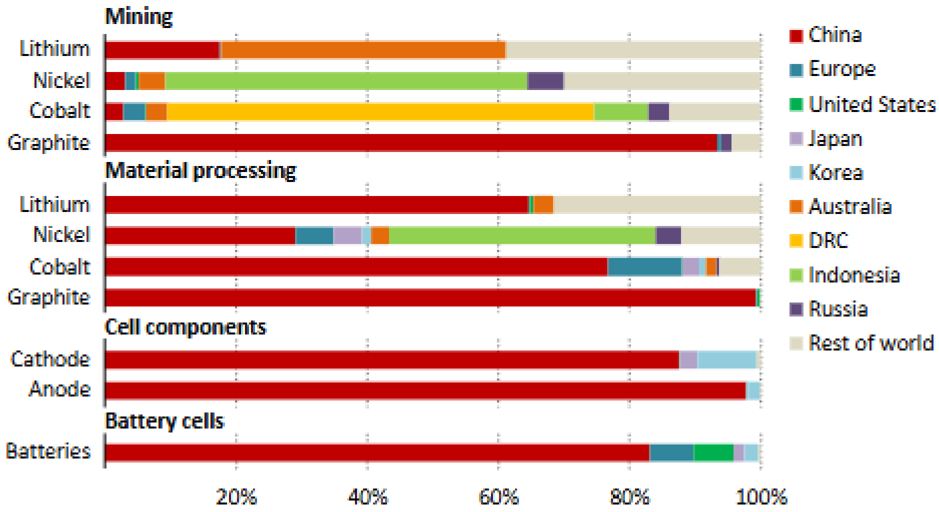

Figure 23. Geographical distribution of the global battery supply[150]

Cell production in the EU is exposed to major supply chain risks, largely because of its strong dependence on imported critical materials (Import dependence on: Lithium – 100%, Nickel – 75%, Manganese – 66%)[152]. To reduce reliance on external suppliers and strengthen its domestic battery industry, the EU has implemented several initiatives, including:

- European Battery Alliance (EBA), fostering industrial cooperation and investment (Building a European battery industry, 2017)
- State aid approvals, with two Important Projects of Common European Interest (IPCEIs) totalling €6,1 billion in public funding, leveraging an estimated €14 billion in private investment (EU, 2024)
- The Critical raw Materials Act, aimed at securing supply chains and reducing dependency on third countries (EU, 2025)

The Net-Zero Industry Act sets a target for the EU to achieve a battery manufacturing capacity of at least 550 GWh by 2030. As of early 2024, the EU appeared on track to meet its 2030 battery targets. However, the bankruptcy protection filing by Swedish firm Northvolt in November 2024 and reports of around 616 GWh of planned capacity being cancelled, delayed, or scaled back have raised concerns about achieving those goals. To stay competitive, the EU needs to accelerate battery production, strengthen and diversify its value chains, increase R&D investment in next-generation technologies, and address key gaps with alternative solutions.

7.2.4 Hydrogen - Electrolysers

Hydrogen, particularly green hydrogen (produced using renewable electricity to split water via electrolysis) and blue hydrogen (produced from natural gas with carbon capture and storage, CCS), is increasingly seen as a key enabler for decarbonising hard-to-abate sectors like industry, heavy transport, and heating in the EU. The EU is aiming to become a global leader in hydrogen

[152] https://www.acea.auto/files/ACEA_Fact_sheet-EU_battery_supply_chain_and_import_reliance_.pdf

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production and use, with an emphasis on scaling up green hydrogen as part of its broader decarbonisation goals. The EU's Hydrogen Strategy for a Climate-Neutral Europe and the REPowerEU plan set targets to produce 10 million tonnes of green hydrogen domestically and to import an additional 10 million tonnes by 2030. Despite these ambitious goals, the hydrogen market in the EU remains at an early stage, with blue hydrogen projects, such as those utilising CCS, playing a significant role in bridging the gap while scaling up renewable energy infrastructure for green hydrogen. However, challenges persist in terms of infrastructure development, cost reduction, and regulatory frameworks.

Hydrogen production today is dominated by fossil-based methods. Over 95% of global hydrogen is currently produced via grey routes—natural gas reforming or coal gasification without carbon capture—resulting in high CO_2 emissions[153]. Green hydrogen, produced through electrolysis powered by renewable electricity, is emerging as the strategic priority in the EU. The REPowerEU plan targets 10 Mt of domestic renewable hydrogen production and 10 Mt of imports annually by 2030 [154] . This focus has increased attention on electrolyser technologies for hydrogen production via electrolysis.

7.2.4.1 Electrolysers technologies

In this section the main electrolyser technologies that have reached high development stages are briefly described and compared according to the key technoeconomics parameters for this such as efficiency, stack lifetime, CAPEX and other main features.

The main technologies for the electrolysers are:

- **Alkaline Water Electrolysers**
- **Proton Exchange Membrane (PEM)**
- **Solid Oxide Electrolysis Cells (SOEC)**
- **Anion Exchange Membrane (AEM)**

Alkaline and PEM electrolysers are the most mature (commercial **TRL 9**), while SOEC and AEM are in pilot or early commercial phase (roughly **TRL 6–7** for AEM, **TRL 7–8** for SOEC) and still scaling up. Each technology has distinct characteristics. **Alkaline electrolysers** use a liquid alkaline KOH electrolyte and nickel-based catalysts; they are long-proven with lifetimes around 80,000 hours, and relatively lower-cost materials (no precious metals)[1]. They operate at < 90°C, typically atmospheric to 30 bar pressure, with electrical efficiency about 60–70% on higher heating value (HHV) basis. Alkaline units have slower responsiveness (ramp times of seconds) and large footprints, but they are readily scaled to multi-MW systems and have the lowest CAPEX among current technologies.

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[153] IEA, 2023; Global Hydrogen Review 2023, https://www.iea.org/reports/global-hydrogen-review-2023
[154] European Commission, 2022; REPowerEU Plan, https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en

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PEM electrolysers instead use a solid polymer membrane (often Nafion) and require precious metal catalysts (platinum at the cathode and iridium at the anode) to withstand the acidic environment. PEM units run at 50–80°C and can efficiently operate at high current densities (1–2 A/cm²), offering flexible operation with rapid response (sub-second) They can handle dynamic power input and are well-suited for variable renewable energy. However, PEM electrolyser CAPEX remains slightly higher due to expensive materials and more complex balance-of-plant and durability is somewhat lower (stack lifetimes ~50,000–80,000 hours before membrane or catalyst replacement).

SOEC electrolysers operate at much higher temperatures (700–850 °C) using a solid ceramic electrolyte (often yttria-stabilised zirconia); this enables the highest electrical efficiency (~80–90%) since part of the energy input is supplied as heat. SOEC technology can produce more hydrogen per kWh of electricity when coupled with industrial waste heat or high-temperature sources. But SOEC stacks have shorter lifetimes so far (<40,000 hours) and are only in the early commercial phase, with a few companies (in Europe and the US) developing multi-MW units. Current SOEC systems are relatively expensive, and they are best suited for steady, high-utilisation operation (e.g. integrated with continuous industrial processes) rather than following variable renewables.

AEM electrolysers are a newer low-temperature type that aims to combine the advantages of alkaline and PEM: they use an anion exchange membrane in alkaline conditions, allowing non-precious metal catalysts (like alkaline) while using a solid membrane (no liquid electrolyte). AEM units promise lower costs and flexibility, but today they exist only at small scale (kW to few MW prototypes) with ongoing R&D to improve durability (current lifetimes and performance are below alkaline/PEM benchmarks).

In summary, alkaline and PEM electrolysers are commercially available and being deployed at large scale, whereas AEM and SOEC are **emerging technologies** that could unlock higher efficiencies or lower costs but still require further innovation and scale-up. Table 15 provides a brief comparison of key characteristics and costs for these technologies.

Table 15. Overview of main water electrolyser technologies (operational parameters and typical 2023 capital costs)

Technology and operating range	TRL	Main Features	Main Cons	CAPEX (Stack)	Efficiency (LHV)	Stack Lifetime (hours)	Main Source
Alkaline **70–90 °C**	9	Low cost; mature tech; robust;	Slow ramp rates; large footprint; liquid electrolyte handling; lower	2,000 USD/kW [155]- 2,250	~60–67% (typical, ~52 kWh_e/kg	80,000	Clean Hydrogen Monitor,

[155] IEA, 2024; Global Hydrogen Review, 2024 (pag 77); https://iea.blob.core.windows.net/assets/89c1e382-dc59-46ca-aa47-9f7d41531ab5/GlobalHydrogenReview2024.pdf

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1-30 bar		long stack life no precious metals; scalable.	current density	EUR/kW[156]	H_2)		2024 IEA Global Hydrogen Review 2024
PEM **50-80 °C** **<70 bar** **(Low-temp 50–80 °C)**	9	Fast response; compact; high purity H_2; suitable for dynamic operation	High CAPEX (~20% more than AEL); Uses rare/expensive iridium/platinum	2,450 USD/kW [3]	~60–70%	~40,000–80,000	
SOEC **(High-temp 700–850 °C)** **1 bar**	7-8	Very high efficiency with heat; suitable for integration with industrial waste heat	Shorter stack life; complex materials; high temp operation limits dynamic use	>2,000 [157]USD/KW expected for large stacks > 1 MW small series production; 5,000 USD/kW)	**Up to ~84%** when supplied with heat ≥650 °C (overall efficiency can exceed 100% LHV with waste heat)	**Shorter** (early-stage; stack longevity in the order of thousands of hours)	**IRENA, 2020. Green Hydrogen Cost Reduction** **Pag.12**
AEM (Anion Exchange) **40-70 °C** **< 35 bar**	6-7	Potential for low cost (no precious metals); flexible; combines PEM and AEL traits	Still early-stage; uncertain durability; limited large-scale demos to date	*Emerging:* costs not yet well-defined (aiming to approach PEM/AEL levels)	60–65% (expected similar to other low-temp systems)	**Developing:** initial stacks on the order of <20,000 hours; commercial targets >50,000 hours	

7.2.4.2 Global and EU Market Share and deployment trends

Globally, installed electrolyser capacity reached approximately 1.4 GW by the end of 2023, with

[156] Clean Hydrogen Monitor, 2024 (pag. 36); https://hydrogeneurope.eu/wp-content/uploads/2023/10/Clean_Hydrogen_Monitor_11-2023_DIGITAL.pdf
[157] IRENA 2020; Green Hydrogen Cost Reduction: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

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China accounting for over 1 GW[158]. Announced projects globally now exceed 500 GW, although only a small fraction has reached final investment decision. In the EU, installed capacity was estimated between 160–500 MW by the end of 2023, with the region rapidly increasing commitments through mechanisms like the EU Hydrogen Bank [159] .

On the manufacturing side, global electrolyser production capacity reached 25 GW in 2023, doubling from 2022. China holds approximately 60% of this capacity, China's advantage stems from concerted government support, economies of scale, and the crossover of big players from the solar industry: for example, major Chinese solar panel firms like LONGi and Sungrow have built large alkaline electrolyser factories. The remaining 40% of global manufacturing capacity is split chiefly between Europe (which constitutes a significant share of current capacity), North America, and a few other Asian nations (Japan, South Korea, India). EU is scaling up with pledged expansions to 17.5 GW per year by 2025[160] .

Within Europe, electrolyser manufacturing is a growing industry with numerous new facilities being built. As of mid-2024, the EU (with UK and EFTA) had 5.4 GW per year of operational electrolyser manufacturing capacity, up from about 3.1 GW per year one year prior. This rapid increase is due to several "gigafactory" investments by European firms. By the end of 2024 the total nameplate capacity in Europe (including plants under commissioning) reached roughly 8.7–10 GW per year, and if all projects under construction come online, Europe's annual manufacturing capacity is expected to rise to around 13 GW/year by 2026.

Electrolysers manufacturing: top players in Europe and globally

Major European electrolyser factories either operational or imminent include: **Thyssenkrupp Nucera's** gigawatt-scale alkaline electrolyser production in Germany (expanded to supply a 2 GW Saudi project); **Siemens Energy'**s new PEM electrolyser plant in Berlin (1 GW/yr capacity opened in 2023); **Nel ASA'**s fully automated alkaline stack plant in Herøya, Norway (up to 500 MW/yr, with expansions underway and a 4 GW/yr factory planned in the U.S.); **ITM Power'**s PEM "Gigafactory" in the UK (target 1.5 GW/yr); Cummins (via its Hydrogenics unit) with PEM factories in Belgium and Spain (500 MW); **McPhy** Energy building a 1 GW alkaline electrolyser plant in France (supported by EU Innovation Fund); **Sunfire** in Germany scaling up both alkaline and SOEC production (500 MW SOEC factory under construction); **Topsoe** in Denmark focusing on SOEC (planned 500 MW/yr by 2025, 5 GW by 2030); and **Enapter** in Italy ramping an AEM mass-production facility (100 MW/yr initial). Thanks to these investments, Europe is home to many of the technology frontrunners and is likely to maintain a strong position in PEM and SOEC manufacturing. By technology, Europe's current manufacturing capacity is roughly balanced between PEM and alkaline – in 2024 about 53% of Europe's production capacity was for PEM electrolysers (4.7 GW/yr) and 46% for alkaline (4.1 GW/yr) with only 1% for SOEC/AEM. By 2026, PEM is expected to represent arounf 45% of

[158] IEA, 2023; Global Hydrogen Review 2023, https://www.iea.org/reports/global-hydrogen-review-2023).
[159] European Commission, 2023; European Hydrogen Bank, https://commission.europa.eu/news/eu-hydrogen-bank-auction-awards-eu721-million-support-renewable-hydrogen-projects-2024-04-30_en).
[160] (IEA, 2023; Global Hydrogen Review 2023, https://www.iea.org/reports/global-hydrogen-review-2023).

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Europe's capacity and alkaline around 44%, with SOEC growing to 8% and AEM 3% as new factories dedicated to these emerging techs come online.

Globally, the electrolyser manufacturing industry is becoming increasingly competitive, with new entrants (especially Chinese firms) rapidly expanding capacity. **China's manufacturers such as PERIC (Beijing), Ningbo Keban, Hydrogen Energy Co (SinoHy), LONGi Hydrogen, and Sungrow** have dramatically scaled up output of alkaline electrolyser stacks, often leveraging automation and low-cost materials. Chinese companies benefit from significant domestic demand (hundreds of MW of orders for large solar-to-hydrogen projects) and government support (e.g. tax incentives, cheap financing), enabling them to produce at lower costs.

Six of the world's top ten electrolyser suppliers in 2024 (by shipment volume) were Chinese companies, although Europe's **Thyssenkrupp Nucera** was ranked first due to its shipment of 1 GW of alkaline electrolysers to Saudi Arabia's NEOM project (one of the largest green hydrogen projects globally). Other leading non-Chinese manufacturers include **Nel** (Norway, specialising in alkaline and PEM), **Plug Power** (USA, PEM electrolyser and fuel cell maker), **Cummins/Hydrogenics** (USA/Canada, PEM and some alkaline), **ITM Power** (UK, PEM), **Siemens Energy** (Germany, PEM), **John Cockerill** (Belgium, large-scale alkaline systems, active in Asia partnerships), **McPhy** (France, alkaline), and **Bloom Energy** (USA, which produces SOEC systems). This diverse set of players indicates that while China currently leads in volume and cost, Europe and the US retain strengths in advanced technology and large integrated project experience.

7.2.4.3 Competitive factors

Cost structure: electricity price

Electricity prices remain the dominant driver of hydrogen production cost, often representing 50–70% of the levelised cost of hydrogen[161]. **For the analysis of this factor please refer to Section 2.**

Policy and Regulation: Despite policy ambition, regulatory complexity remains a barrier. RED III delegated acts define stringent criteria for what qualifies as 'renewable hydrogen[162]. These include additionality, temporal, and geographic correlation with renewable electricity, factors that if will remain so strict could increase project complexity and costs. Further, permitting remains slow despite recent legislative efforts, and a lack of harmonised certification schemes for Guarantees of Origin adds uncertainty[163]

Infrastructure and standards

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[161] IRENA, 2023; Green Hydrogen Cost Reduction, https://www.irena.org/publications/2023/Sep/Green-hydrogen-cost-reduction

[162] European Commission, 2023; Delegated Acts on Renewable Hydrogen, https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules_en.

[163] CertifHy, 2024; https://www.certifhy.eu/).

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Building a hydrogen value chain requires new infrastructure (electrolyser factories, large-scale storage, pipelines). The EU's Gas Decarbonisation Package (Aug 2024) created a regulatory framework for dedicated H_2 grid but permit approvals for pipelines and storage also face opposition. Additionally, a shortage of domestic electrolyser factories means Europe depends on imports or foreign investment, in contrast to China or the US, which heavily subsidise local manufacturing/ The EU has introduced public funding (IPCEIs, hydrogen bank) to help, but the scale-up challenge is unprecedented.

In summary, Europe's position in the global electrolyser value chain is one of strong technological know-how but growing competitive pressure. European companies pioneered many electrolyser innovations and remained at the forefront in high-efficiency PEM and SOEC designs, and large-scale project integration. The EU also has a relatively robust domestic market emerging, thanks to ambitious climate targets and subsidies, which can support local manufacturers. However, the rise of Chinese overcapacity with state-backed firms rapidly scaling up and driving costs down – poses a serious threat similar to what transpired in solar panels. Without coordinated action, European manufacturers could lose market share to cheaper imports.

7.2.5 Other clean energy technologies

7.2.5.1 Carbon Capture and Storage (CCS)

Carbon Capture and Storage (CCS) is a set of technologies designed to capture carbon dioxide (CO_2) emissions from industrial processes or power generation before they reach the atmosphere. CCS involves three main steps[164]:

1. **Capture**: CO_2 is separated from gases produced in industrial processes, such as cement or steel production, or from burning fossil fuels. Capture methods include post-combustion (after burning), pre-combustion (before burning), and oxy-fuel combustion (burning in oxygen).
2. **Transport**: Once captured, the CO_2 is compressed and transported, usually by pipeline or ship, to a storage site.
3. **Storage**: The CO_2 is injected deep underground into geological formations, such as depleted oil and gas fields or deep saline aquifers, where it can be securely stored for thousands of years.

Some advanced CCS systems also explore **utilisation** (CCUS), where captured CO_2 is used to make products like fuels, chemicals, or building materials.

Within the EU, Carbon Capture and Storage (CCS) currently plays a very small role in emissions reductions and has a negligible contribution to emissions abatement. In 2024 across Europe there were five projects in operation, with 10 in construction[165], representing 5% of total global

[164] https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage
[165] https://www.globalccsinstitute.com/wp-content/uploads/2024/11/Global-Status-Report-6-November.pdf

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capacity[166], although the EU's Net-Zero Industry Act sets a goal of achieving at least 50 million tonnes of CO_2 annual storage capacity by 2030. Persistent barriers include high capital and operational costs, complex permitting procedures, public acceptance issues, and an underdeveloped CO_2 transport and storage network. As a result, CCS's market penetration in the EU remains far below levels needed for the EU's 2050 climate neutrality targets.

7.2.5.1.1 Manufacturing capacity

The EU's manufacturing capacity for CCS systems is growing but remains insufficient to support the rapid scale-up envisioned in European climate strategies. It is noteworthy that a functioning market for CCS equipment is still largely absent, as also reflected by the low deployment numbers shown in Figure 13. Current industrial production mainly covers CO_2 capture technologies for specific sectors, along with pipeline infrastructure components, primarily based in Germany, Italy, and the Netherlands[167]. Initiatives like the North Sea offshore storage projects are expanding demand for specialised equipment, but the fabrication of absorbers, compressors, and CO_2 transport vessels is still relatively fragmented and concentrated among a few specialised firms. Without accelerated investment in supply chains, standardisation efforts, and workforce development, the EU risks facing significant bottlenecks that could delay achieving its CCS deployment and emissions reduction goals.

7.2.5.1.2 CO_2 infrastructure

Pipelines are essential for transporting captured CO_2 from industrial sources to storage sites or utilisation facilities. Significant initiatives like the CO2TransPorts[168] project aim to establish infrastructure connecting major European ports, facilitating large-scale CO_2 capture, transport, and storage. By 2030, Europe plans to have over 160 million tons of CO_2 storage capacity, primarily around the North Sea[169]. Projects such Porthos initiative in the Netherlands and the Greensand[170] project off Denmark's coast are leading examples. The Porthos[171] project aims to inject[172] up to 1,5 million tonnes of CO_2 annually into depleted gas fields beneath the North Sea, with operations expected to commence by late 2025 or early 2026.

Those projects show EU's capability to not only develop but also commercialise cutting-edge technologies for capturing and storing CO_2. The scalability of such technologies along with integrated solutions (e.g. liquefaction, injection and transportation), strengthens the EU's position as a leader in the global clean tech market.

[166] https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage
[167] https://cembureau.eu/innovation/map-of-innovation-projects/
[168] https://ec.europa.eu/assets/cinea/PCI/files/PCIFiche_13.1_1st_PCI_PMI_list.pdf
[169] https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co2-transport-and-storage
[170] https://www.globalccsinstitute.com/news-media/latest-news/denmarks-project-greensand-begins-groundbreaking-cross-border-co2-injection/
[171] https://www.porthosco2.nl/en/project/
[172] Injection facilities are designed to permanently store CO2 in geological formations.

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7.2.5.2 Heat pumps

Heat pumps are cornerstone of building decarbonisation strategies, replacing fossil fuel-based heating systems. Governments are increasingly offering subsidies, tax incentives and stricter efficiency regulations to accelerate adoption.

7.2.5.2.1 Market share

The heat pump market has experienced significant growth over recent years. In 2022, the global market revenue reached more than $60 billion[173] (Tajammul Pangarkar, 2025) with key regions contributing as shown in Figure 2. As the largest market, China benefits from aggressive government policies promoting electrification and building efficiency. The expansion of district heating systems and industrial applications further boosts demand. Government subsidies and mandates for heat pump installations in new buildings have accelerated adoption. Heat pump sales grew by 20% year-on-year in 2023[174], reinforcing the country's leadership in absolute revenue and volume.

China continues (in 2025) to dominate due to its manufacturing capacity and large-scale adoption, while Europe leads in technological advancements and high-performance heat pump solutions. North America's market share is expected to expand as government incentives gain traction.

The levelised cost of production (LCOP) for air-to-air heat pumps is significantly lower in China (50% cheaper than in US and 40-60% than the EU). The key drivers of these cost differences include labour costs (which represent 10-15% of LCOP) and component sourcing (accounting for 60-80% of LCOP). While labour costs in Europe are higher, the main challenge for EU competitiveness lies in sourcing lower-cost components.

7.2.5.2.2 Manufacturing capacity

The EU has made significant progress in developing its heat pump manufacturing capacity, particularly in Central and Eastern Europe. Key manufacturing hubs are emerging in countries such as Poland, the Czech Republic and Slovakia. In 2022, global heat pump manufacturing capacity was led by China, which had an impressive 50GW of production capacity. The US followed with 34GW while the EU had 25GW. China (with its larger manufacturing capacity) presents a challenge for the EU, supported by lower labour costs and economies of scale. Nevertheless, the EU's focus on high-quality products and innovation gives it an edge in meeting growing demand for energy efficient, low-carbon solutions.

7.3 Supply Chain

Clean technology manufacturing is highly material-intensive, requiring substantial inputs of critical and strategic raw materials. Lithium, cobalt, nickel, rare earth elements and cooper are among the essential materials needed for batteries, wind turbines and electric vehicles. Currently, the EU

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[173] https://www.news.market.us/heat-pump-statistics/
[174] https://www.iea.org/commentaries/is-a-turnaround-in-sight-for-heat-pump-markets

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sources a significant share of these materials from a handful of external suppliers, notably China, Chile, Australia and the Democratic Republic of Congo. The Critical Raw Materials Act (CRMA), introduced by the European Commission, aims to mitigate these dependencies by increasing domestic extraction, refining and recycling capacities. However, the EU faces challenges in scaling up mining operations due to environmental concerns and long permitting processes. Consequently, securing stable and diversified supply chains through international partnerships remains a priority.

The transition to clean energy technologies is placing increasing pressure on global supply chains, particularly for critical raw materials. Ensuring secure and sustainable access to these materials is becoming a key challenge for energy transition strategies, especially for regions like the European Union (EU), which is heavily dependent on imports for many of these resources. Table 16 outlines the main raw materials required across various clean energy technologies, such as solar, wind, and electric vehicles, highlighting the growing reliance on specific resources and the associated implications for international trade and supply security within the EU and globally.

Table 1616. Key materials for clean energy technologies, Data Source: (Energy Transitions Commission, 2023)

	Solar	Wind	Power Grids	Electric Vehicles & Batteries	Hydrogen Electrolysers	Nuclear	Hydropower
Aluminum	☑	☑	☑		☑		☑
Cobalt				☑			
Copper	☑	☑	☑	☑	☑	☑	☑
Graphite (for Anodes)				☑			
Lithium				☑			
Neodymium		☑		☑		☑	
Nickel		☑		☑	☑	☑	☑
Palladium and Platinum					☑		
Polysilicon	☑						
Silver	☑						
Steel	☑	☑	☑		☑	☑	☑
Uranium						☑	

As the global demand for clean technologies surges, the EU must ensure that its supply chains are not only resilient but also sustainable. The push for a circular economy, where recycling and material recovery play a larger role, is central to reducing import dependency.

7.4 Roadmap of clean technology manufacturing in EU

7.4.1 EU vulnerabilities

To assess supply chain vulnerabilities of key clean energy technologies in the EU, a multi-source literature review of authoritative sources was performed. To ensure comparability and scientific rigor, the analysis was structured around three core indicators: i) import dependence (%), ii) supplier concentration, iii) EU production capacity. These indicators were defined and operationalised as follows:

i) import dependency reflects the degree to which a technology or its critical components (e.g., rare earth elements, wafers, semiconductors) rely on imports from outside the EU. This was rated using data on trade balances, origin of raw critical materials, primarily from IEA's Energy Technology Perspectives 2023[175], IEA's Solar PV Global Supply Chains 2022[176], the European Commission's Supply Chain Risks in the EU's Clean Energy Technologies 2023[177] and the DG Grow's Raw Materials Scoreboard[178].

ii) Supplier Concentration captures the extent to which global supply chains are dominated by a small number of companies or countries. Ratings were informed by global market share data, concentration ratios (e.g. >60% supplied by one country = 'very high'), and critical material supply chain mappings from IEA[179], IRENA's Critical Materials for the Energy Transition, and the EU's Critical Raw Materials Act.

iii) EU Production Capacity assesses the current level of manufacturing or extraction capacity within the EU. Data were drawn from Eurostat, 2025, European Commission RMIS – Raw Materials Information System, 2021, European Commission, 2020, industry white papers (e.g. European Battery Alliance[180] , RePowerEU updates[181].

The supply chain for batteries, heat pumps, wind, solar, hydrogen, exhibit varying degrees of vulnerability due to import dependence, supplier concentration and limited domestic production (Table). The battery sector faces the highest risks, with nearly 100% reliance on imports for key materials such as lithium, cobalt, and nickel, with processing heavily concentrated in China. Similarly, the solar industry is highly exposed, with 97% of global wafer and ingot supply controlled by China, leaving the EU with minimal production capacity.

For the wind turbines, the situation is slightly less critical but still concerning. The EU has strong manufacturing capabilities, yet it remains dependent on China for rare earth elements used in generators. Hydrogen production, particularly electrolysers, depends on platinum and iridium, sourced mainly from Russia and South Africa, creating potential supply risks. Electrolyser

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[175] https://www.iea.org/reports/energy-technology-perspectives-2023
[176] https://www.iea.org/reports/solar-pv-global-supply-chains
[177] https://data.europa.eu/doi/10.2833/818557
[178] https://data.europa.eu/doi/10.2873/567799
[179] https://www.iea.org/reports/global-critical-minerals-outlook-2024
[180] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0643&qid=1669913060946
[181] https://energy.ec.europa.eu/publications/repowereu-2-years_en

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production requires at least 40 raw materials, and the EU currently produces just 1-5% of these domestically[182]. Heat pumps face lower vulnerabilities, as supply chains are more diversified, but component dependencies still exist.

To illustrate these vulnerabilities, Table 17 provides a rating system evaluating each clean technology across three key risk factors: import dependency, supplier concentration, and EU production capacity.

Table 1717. Supply chain vulnerabilities in key clean technologies[183]. The rating in this table was developed using three key indicators: i) import dependence (%), ii) supplier concentration, iii) EU production capacity.

Technology	Import Dependence	Supplier Concentration	EU production Capacity	Key Risk areas
Batteries	★★★★	★★★★	★	Lithium, cobalt, nickel, refining is highly concentrated in China
Wind turbines	★★	★★★	★★	Rare earth elements for generators, mainly from China
Solar panels	★★★★	★★★★	★	97% of ingot & wafer supply is controlled by China
Hydrogen	★★★	★★	★	Platinum and iridium for electrolysers from Russia and South Africa
Heat pumps	★	★★	★★	Component supply risks, but less documented vulnerabilities

Rating: ★ *(Low),* ★★ *(Moderate),* ★★★ *(High) iv),* ★★★★ *(Very high)*

7.4.2 EU strategies to reduce dependencies on critical materials

The EU has recognised the increasing risk associated with supply chain dependencies for critical materials essential for the clean energy transition. As demand for materials such as lithium, rare earth elements and cobalt continues to grow due to the rapid expansion of clean technologies (battery technologies, wind turbines, solar panels, hydrogen electrolysers, heat pumps), the EU has taken significant steps to enhance energy security. The following strategies form the core of

[182] https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en

the EU's approach to reducing dependency and strengthening its position in the global energy transition.

The Critical Raw Materials Act (CRMA), alongside industrial alliances, trade agreements, and circular economy policies, forms the foundation of Europe's approach to securing this access (to vital raw materials). The EU's strategy focuses on five key areas: enhancing domestic production, diversifying external supply sources, strengthening supply chain resilience, promoting recycling and circular economy initiatives, and investing in R&D for material substitution.

7.4.2.1 The role of CRMA

The Critical Raw Materials Act (CRMA) aims to boost the EU's industrial competitiveness by securing a stable supply of essential raw materials, reducing dependency on a few countries like China. It sets targets for extraction, processing, and recycling within the EU and supports strategic projects, faster permitting, and international partnerships. This strengthens industrial resilience and reduces risks for sectors crucial to the green and digital transitions. Table 18 lists the main pillars of CRMA, along with the key measures and expected impacts.

Table 1818. The role of CRMA in securing EU supply chains

CRMA pillar	Key measures	Expected impact
Boosting domestic supply	- 10% of annual EU demand for critical raw materials must be extracted in the EU - 40% of demand to be processed in the EU - 15% of demand to be met through recycling	- reduces reliance on third countries - strengthens EU production capacity
Diversification of imports	- strategic partnerships with resource-rich countries (e.g. Canada, Australia, Namibia) - Trade agreements for stable supply chains	- lowers risks of supply disruptions - increases resilience against geopolitical risks
Streamlining permitting	- accelerated approval for mining and refining projects - EU-wide coordination to speed up investments	- reduces project delays - encourages private sector participation
Recycling and circular economy	- mandatory recycled content in key technologies (batteries, magnets) - strengthened urban mining initiatives	- lowers dependency on virgin materials - reduces environmental footprint

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Supply chain monitoring	- early warning system for disruptions - strategic stockpiling of critical materials	- improves market transparency - ensures crisis preparedness

7.4.3 Clean Industrial Deal

The Clean Industrial Deal is a strategic vision to align the EU's climate goals with industrial competitiveness, focusing on supporting the decarbonisation of energy-intensive industries, which require a steady and secure supply of clean and affordable energy, and scaling up clean-tech manufacturing. It builds on the EU's ambition to become a global leader in clean-tech manufacturing by strategically aligning industrial, climate, and energy policies and seeks to create a favourable environment for producing key net-zero technologies within Europe, such as solar panels, wind turbines, batteries, and heat pumps.

Substantial public and private investments are being mobilised to meet the EU's goal of manufacturing at least 40% of its clean tech needs domestically by 2030 (NZIA). The Clean Industrial Deal aims to mobilise over 100 billion euros in public and private investments to support EU-made clean technologies, including solar panels, wind turbines, batteries, heat pumps, and electrolysers. This funding is facilitated through several key initiatives, Industrial Decarbonisation Bank, InvestEU Enhancements, and Innovation and Research Funding. In addition to financial instruments, the Clean Industrial Deal emphasises the importance of a skilled workforce. Through the Erasmus+ program, up to 90 million euros will be allocated to reinforce education and training programs, addressing skills shortages in key sectors and ensuring a competent workforce to support the clean transition.

By integrating these measures, the Clean Industrial Deal seeks to enhance the EU's industrial resilience, reduce dependencies on external suppliers, and position Europe as a global leader in clean technology manufacturing.

8 Circular Economy integration in models

Circular Economy (CE) aims to decouple economic activity from resource use by extending product lifespans, increasing reuse and recycling, and minimising waste. As governments and international organisations increasingly adopt CE strategies to achieve sustainability and climate goals, it becomes imperative for modelling tools to capture these dynamics[184]. However, traditional macroeconomic models such as CGE models and energy system models are not inherently designed to reflect CE principles. Enhancing these models to better reflect CE strategies and measures, requires the introduction of new assumptions, parameters, and mechanisms that can account for structural changes in the consumption, production, and technology.

This section presents a structured discussion on how CE measures, particularly those affecting material flows and product composition of demand, can be incorporated into computable general equilibrium (CGE) models and energy system models. Rather than relying solely on physical tracking, the focus is on systemic changes in economic structure, demand behaviour, and policy representation.

8.1 Integration of circular economy strategies in socioeconomic models

CGE models are powerful macroeconomic tools used to simulate how economies respond to policy, technology, and behavioural changes. They capture intersectoral dependencies, price dynamics, labour and capital market developments, and trade effects, making them well-suited to assess CE strategies' economy-wide impacts, provided their structure is adapted accordingly.

Sector Disaggregation and Structural Change
Circular economic activities often emerge as new sectors (e.g., repair, leasing, recycling, or remanufacturing services) or gain increasing economic importance. Introducing these explicitly allows the model to shift value creation across activity sectors while changing from linear to circular modes. For example, a transition from purchasing new goods to service-based use (like car-sharing) would reduce demand for car manufacturing while increasing transport services and maintenance sectors. This also allows for simulating structural change in final demand, where consumption shifts toward labour-intensive circular services instead of material- and energy-intensive goods. By disaggregating input–output tables or social accounting matrices to reflect such sectors, CGE models can better represent the redistribution of value added and employment induced by CE strategies.

Substitution Between Primary and Secondary Materials
Circular strategies often involve replacing virgin materials with recycled or reused inputs. CGE models can reflect this by modifying production functions to allow substitution between primary and secondary inputs (e.g. primary and secondary steelmaking). This substitution can be

[184] https://climate.ec.europa.eu/document/download/dc751b7f-6bff-47eb-9535-32181f35607a_en?filename=com_2018_733_analysis_in_support_en.pdf

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calibrated with elasticities that reflect the ease of replacement, production costs, and market competitiveness. Introducing secondary material markets, even without full material tracking, allows the exploration of how policies (e.g., recycled content mandates or landfill taxes) influence production costs, resource use, emissions, and trade flows.

Demand-Side Behavioural Shifts

Changes in consumption patterns are a cornerstone of circularity. CE measures that encourage product longevity, reuse, or service-based consumption (e.g., renting instead of owning) fundamentally alter household utility. CGE models can capture these shifts by adjusting utility functions, incorporating non-material utility preferences, or redefining consumption baskets to include shared or repaired products. Additionally, policies such as right-to-repair legislation or eco-labelling can influence consumer preferences towards CE options, which can be simulated by changing demand elasticities or incorporating differentiated product choices.

Resource Efficiency and Waste Management

Production efficiency improvements and waste reductions are often key targets of circular strategies. CGE models can integrate these through total factor productivity changes, differentiated input requirements, or the introduction of waste treatment sectors. For instance, recycling sectors can generate inputs to production and reduce landfill use, influencing both costs and environmental externalities. While detailed material flow tracking is not intrinsic to CGE models, simplified representations (e.g., proxy indicators or environmental extensions) can be applied to monitor material intensity and waste generation trends.

Policy Instruments

A range of CE policies can be integrated into CGE models, including product taxes or eco-design requirements that influence manufacturing processes, recycling or reuse subsidies that shift relative prices, extended producer responsibility that redistributes costs across value chains. Such instruments can be modelled as changes in cost structures, taxes, or subsidies, allowing for analysis of efficiency, competitiveness, and equity outcomes.

8.2 Integration of circular economy strategies in energy models

Energy system models capture the complex interplay between energy supply and demand, providing projections of future energy demand, supply, power generation mix, carbon emissions, energy prices, and investment across different pathways. While their traditional focus is on shifting among fuels, power generation mixes, and demand-side efficiency, they can be extended to reflect CE strategies that influence both material use and energy demand.

Reduced Demand via Circular Services

Circular strategies that reduce material throughput, such as product sharing, lifetime extension, or dematerialisation, have direct implications for energy demand. These strategies can be incorporated by modifying demand trajectories for specific energy services. For example, scenarios that assume extended product lifespans or increased reuse can lower energy demand and activity associated with manufacturing and logistics (i.e. reduced production of steel or cement, reduced freight transport activity).

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Efficiency Gains and Embedded Energy Reduction

A key feature of circular strategies is improving the efficiency with which resources and products are used. In energy system models, this can be reflected in lower energy inputs per unit of service delivered (i.e. increased efficiency) or through assumptions about declining embedded energy in manufactured goods due to increased recycling and reuse. Adjustments in technology and efficiency-related parameters can reflect these shifts.

Circular Supply Chains and Resource Substitution

Energy technologies can also be modelled to substitute primary materials with recycled ones, impacting both the energy intensity and environmental footprint of production. While detailed tracking of materials may be limited in such tools, models can apply scalar adjustments to reflect improvements in material circularity or introduce constraints on virgin resource availability to stimulate substitution.

Scenario-Based Policy Representation

Circular economy policies that affect the energy system, such as material efficiency standards, product passports, or recycling targets, can be represented in energy system models through scenario assumptions. These may include changes in cost curves, efficiency parameters, demand projections, or emissions constraints. Although stylised, such scenario approaches allow exploration of system-level impacts.

8.3 Coupling with material flow analysis

Linking socioeconomic or energy models with material flow analysis improves the understanding of circular economy impacts, an approach which will be followed within the MIC3 framework. MFA adds a physical perspective, allowing models to assess resource use, recycling, and material efficiency. This coupling can identify supply risks, quantify material savings, and evaluate environmental benefits. Integration can be done via satellite accounts or scenario alignment. Though more complex, this approach ensures circular strategies are assessed both economically and materially, supporting more realistic and comprehensive planning.

9 Conclusions

This deliverable has provided a comprehensive assessment of the challenges and opportunities faced by key EU industrial sectors, iron and steel, cement, chemicals, and clean technologies, in their pursuit of climate neutrality and sustained competitiveness. The findings underscore the complex interplay between technological innovation, cost structures, regulatory frameworks, and market dynamics shaping the EU's industrial transformation.

9.1 Sectoral Decarbonisation Pathways and Challenges

Each sector exhibits distinct decarbonisation pathways rooted in their unique production processes and energy requirements. The iron and steel sector's transition hinges on scaling breakthrough technologies such as hydrogen direct reduction and enhanced electric arc furnace usage. These approaches promise significant emissions reductions but demand substantial capital investment and stable hydrogen supply chains. The cement industry faces even more profound challenges due to its inherent process emissions and energy intensity. Mitigation here will require a multifaceted strategy combining alternative clinker materials, carbon capture and storage (CCS), and electrification, all requiring coordinated R&D and infrastructure development.

The chemicals sector's pathway to net-zero is characterised by diversification, leveraging electrification, green hydrogen, and feedstock substitution. However, the sector's heterogeneous nature means solutions must be tailored to specific product lines and end-uses, emphasising innovation agility and cross-sector collaboration. Clean technologies emerge as pivotal enablers across all sectors, offering efficiencies, digitalisation benefits, and process improvements that support overall industrial decarbonisation.

9.2 Enabling Conditions and Policy Implications

Beyond technology, the report highlights enabling conditions critical for success, including access to raw materials, energy affordability and reliability, skilled labour, and investment certainty. The interplay of CAPEX and OPEX factors reveals the importance of financing mechanisms and cost containment strategies to prevent competitiveness erosion.

EU-wide policy frameworks such as the ETS and CBAM are central to this transition, incentivising emission reductions while aiming to guard against carbon leakage. However, policy design must balance stringency with flexibility to ensure that decarbonisation efforts do not inadvertently accelerate industrial relocation outside the EU, thereby undermining climate ambitions. Integration of circular economy principles, enhanced digitalisation, and workforce reskilling are also essential complements to regulatory measures.

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9.3 Strategic Outlook

In conclusion, the EU's industrial sectors face a decisive juncture where proactive investments and coherent policies can position them as global leaders in the low-carbon economy. Achieving climate neutrality demands long-term vision, multi-stakeholder cooperation, and agility in adapting to evolving technological and market conditions. The recommendations presented advocate for a holistic approach that not only reduces emissions but also enhances resilience, innovation capacity, and global competitiveness.

Sustained commitment from public and private actors will be vital to navigating the transition's complexities. By fostering an environment conducive to innovation, ensuring equitable access to resources, and safeguarding competitiveness, the EU can realise an industrial future that is sustainable, resilient, and prosperous

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