Reviving Europe's Industrial Power:
How to boost competitiveness through energy

With the scientific contribution of the

Foundation

ERCST
Roundtable on Climate Change and Sustainable Transition

A study by Compass Lexecon

09 December 2024

COMPASS LEXECON

Table of Contents

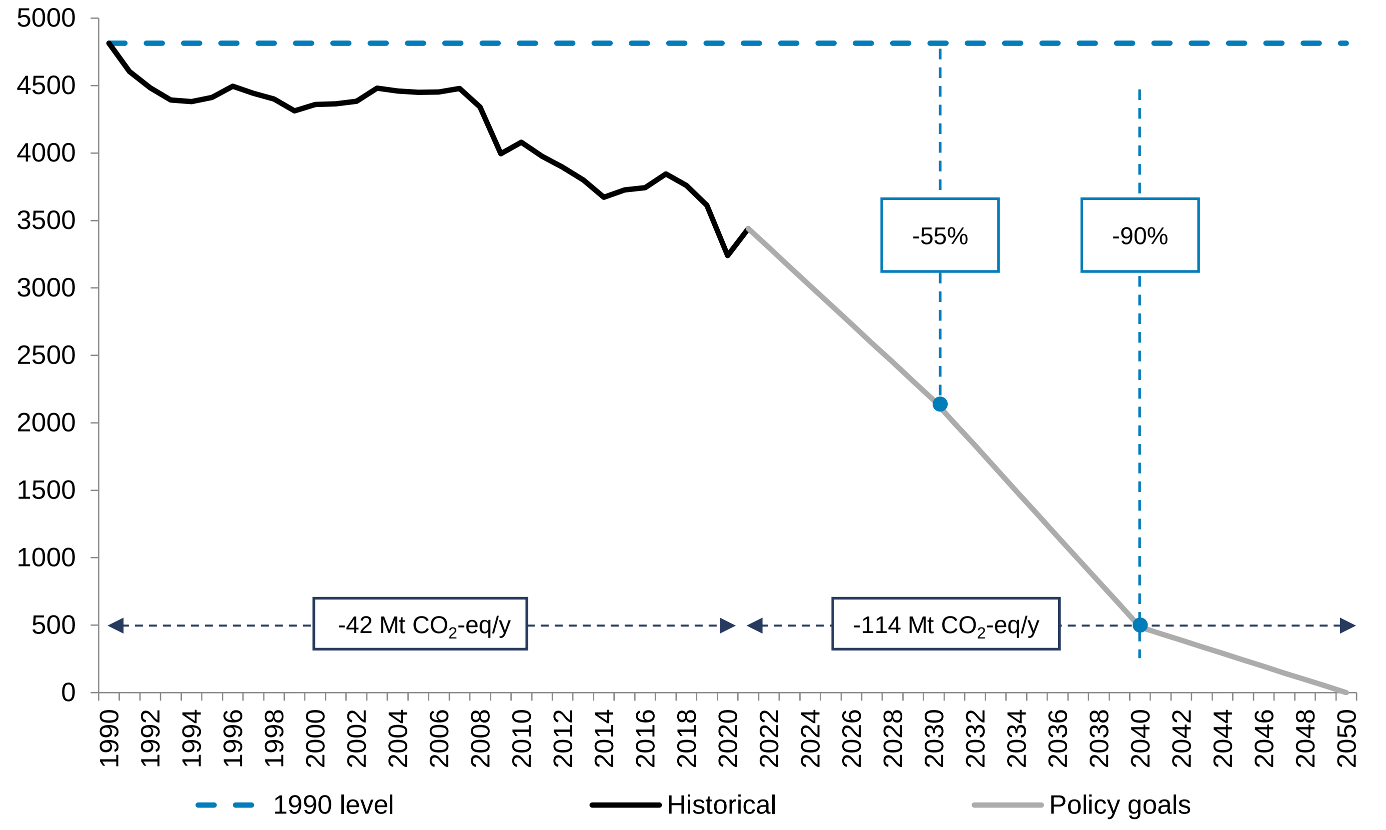
1. Introduction

The EU needs to decrease its GHG emissions three times faster than historically by 2050 while maintaining its industrial competitiveness

The EU has pledged to cut GHG emissions and achieve climate neutrality by 2050 which will require low-carbon energy supply and an electrification of end-uses.

- In the wake of the Paris Agreement of 2015, the EU is aiming for Net-Zero emissions by 2050 and has developed a policy and regulatory framework to foster the energy transition.
- The Green Deal, via the EU Climate Law adopted in 2021, targets a reduction of net GHG emissions by at least 55% by 2030, compared to 1990 levels. A further goal of 90% less emissions by 2040 was recommended in the EC's 2040 Climate Target Impact Assessment published in 2024.
- To achieve Net-Zero targets by 2050, low-carbon energy is being deployed across Europe, and a massive electrification of end-uses is planned.
- With the power sector's decarbonisation challenges and low-carbon technologies being well-understood and the transition already underway, attention is increasingly shifting to industrial decarbonisation as the next critical step, facing significant hurdles related to maintaining competitiveness.

Total annual GHG emissions, including LULUCF & CCS – EU-27, 1990-2050 (Mt CO_2-eq)



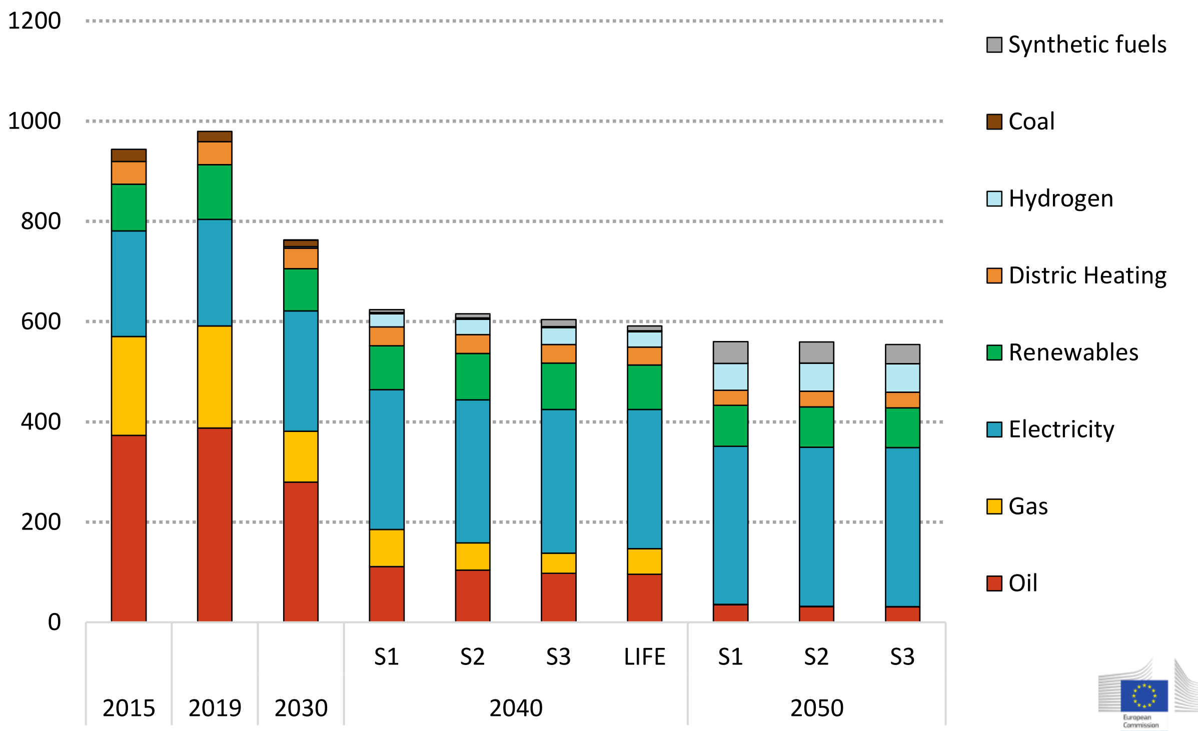
Source: Compass Lexecon analysis based on the Paris Agreement (2015); the European Green Deal (2020); EC's 2040 Climate Target Impact Assessment (2024); EU Strategy for Energy System Integration (2020).
Abbreviations: GHG: Greenhouse Gases; LULUCF: Land Use, Land Use Change and Forestry; CCS: Carbon capture and storage.

Achieving deep electrification of energy end-uses, both directly and indirectly, is critical for decarbonising the EU economy

Electricity is expected to increasingly dominate the future energy in all projected scenarios of the EC's 2040 Climate Target Impact Assessment published in 2024.

- Electrification is expected to play a growing and critical role in the decarbonisation of the EU economy, ending a decades-long reliance on fossil fuels as the predominant carrier of energy.
- The EC projects that electricity will be the single largest energy carrier by 2050, supplying 60% of final energy consumption excluding feedstock in the EU. hydrogen and other renewables are also expected to be essential as complementary energy sources.
- Based on the EC's scenarios, electricity grids are thus set to become the backbone of the EU energy system.
- However, the electrification of end-uses requires the uptake of electric vehicles, heat pumps in residential heating and cooling, and the competitiveness of electrified processes in the industry.

Final energy consumption by energy carrier – EU-27, 2015-2050 (Mtoe)



Source: European Commission (2024), 2040 Climate Target Impact Assessment

The EU's progress towards Net-Zero emissions is facing challenges from energy supply to end-uses – this study focusses on the decarbonisation of EU manufacturing industries

- Challenges in achieving EU climate neutrality span the entire range of EU activities related to energy consumption and production.
- In this study, we focus on the decarbonisation of the industry, in particular on manufacturing sectors.

Focus of the analysis

Electricity generation	Industrial activity	Heating and cooling for buildings	H_2 Hydrogen production
The electrification of end-uses will require a **substantial increase in the production of and access to low-carbon electricity at an affordable cost**, in a complex and challenging environment due to: ▪ Challenges linked to the acceleration of low-carbon electricity development and energy efficiency ▪ The growing need for flexibility and additional investments in power grids ▪ The challenge of nuclear power plants' life extension and refurbishing	In manufacturing industries, the decarbonisation of **each process requires a case-by-case approach to address the economic and non-economic challenges:** ▪ **Cost issues and technological limitations** that could hinder process electrification ▪ Some industrial applications **not yet suited to direct electrification,** but with possible reliance on low-carbon heat or hydrogen ▪ Other regulatory and/or technical constraints that might hamper decarbonisation	Decarbonising the heating and cooling of residential and tertiary buildings will need to address current challenges and rely on: ▪ The electrification and efficiency gains made possible by heat pumps ▪ The development of district heating and cooling ▪ Fostering high-performance thermal renovation	The need to produce or import carbon-free hydrogen is expected to increase in the long-term, particularly for: ▪ Using hydrogen as a feedstock ▪ The production of electrofuels (e-fuels) in aviation and maritime transport ▪ Providing flexibility and storage for power systems ▪ Decarbonising industrial processes

The decarbonisation of the economy must take place while **considering the specific needs of regions** and **under both ecological and socio-economic constraints**

Biodiversity and ecosystems	Preservation of soil and water resources	Facilitate financial credits	Industrial competitiveness and reindustrialisation	Preservation/ creation of jobs	Strategic independence and supply chains

Source: Compass Lexecon analysis
Note: The list of ecological and socio-economic constraints is not exhaustive.
Note: A distinction should be made between socio-economic constraints linked to overarching economic orientations of the EU and non-economic barriers attached to specific sectoral issues hampering the development of low-carbon manufacturing processes domestically.

The study focuses on decarbonisation of industry with a particular focus on the economic challenges and possible supporting policies and measures

4 core phases of the study	Hybrid methodology		3 complementary organisations
Technical potential for direct and indirect electrification	▪ Focus on large industrial manufacturing sectors (food and beverages, metallurgy, chemicals, etc.) ▪ Statistical analysis of manufacturing industries' shares in emissions, GVA, energy use, etc. ▪ Meta-analysis of studies on the technical potential for direct and indirect electrification		COMPASS LEXECON Drafting of the report Qualitative and quantitative analysis Research on barriers, policy frameworks, and support mechanisms Support in consultations, drafting questionnaires
Economic potential for direct and indirect electrification	▪ Bottom-up modelling of energy production costs for selected process heating-based applications in manufacturing industries in the EU, with a sanity check through the consultation of stakeholders	Stakeholders' engagement through: ▪ Bilateral interviews ▪ Written consultation ▪ 2 in-person consultation workshops	ERCST Roundtable on Climate Change and Sustainable Transition Listing and initial reach-out to stakeholders Conducting bilateral interviews Reviewing feedback from stakeholders Support in drafting
Barriers to industrial electrification	▪ Review of economic and non-economic barriers, such as lock-in risks, technological challenges, insufficient grid infrastructure, regulatory uncertainties, supply chain issues, structural limitations		enel Foundation Study steering Support in drafting and consultations
Support mechanisms for industrial electrification	▪ Review of possible approaches and measures to lift non-economic barriers, secure the supply of abundant competitive low-carbon energy, and bridge the lack of a business case when relevant		

+

Enel Foundation's policy recommendations — enel Foundation

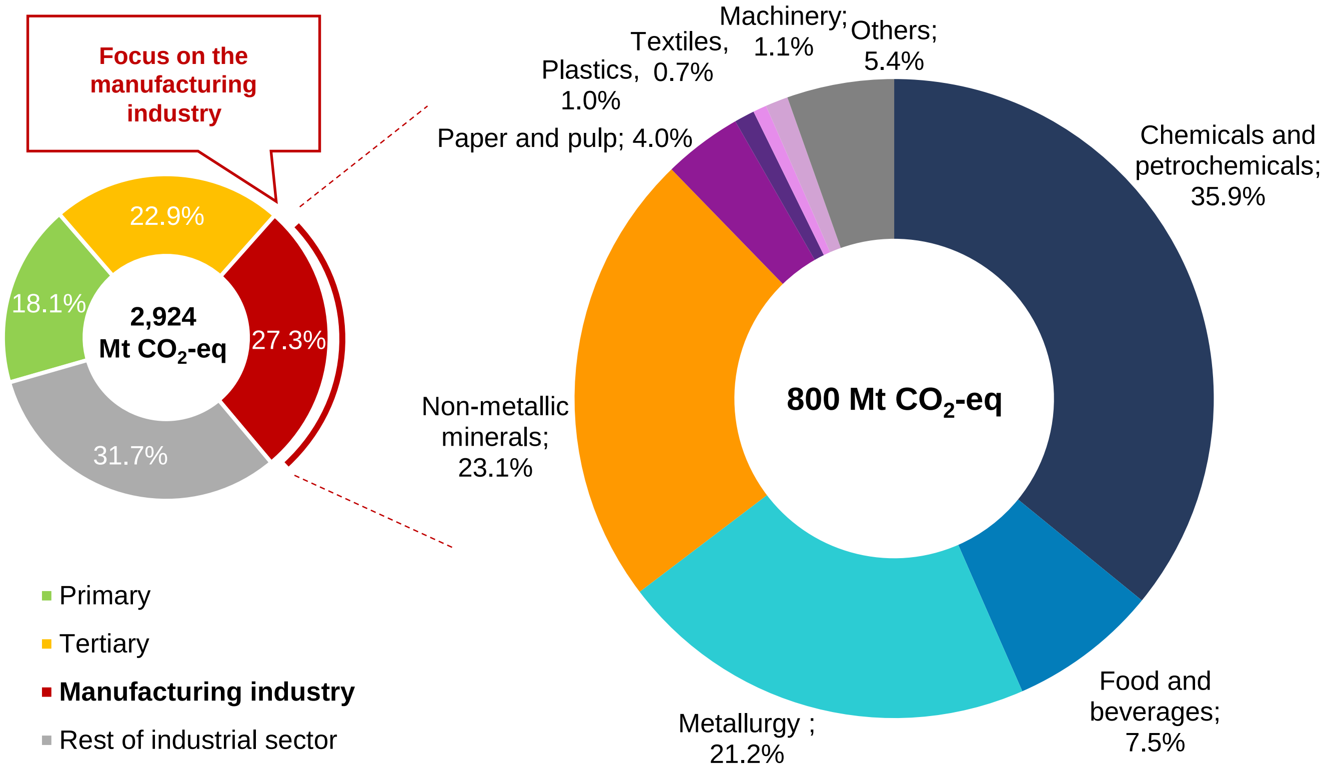
Source: Compass Lexecon analysis

2. Technical and economic potential for electrification in EU manufacturing industries

2.1 State-of-play of EU manufacturing industries

Manufacturing industries accounted for 27% of total EU GHG emissions in 2021, with chemicals, non-metallic minerals and metallurgy accounting for 80% of those

Total GHG emissions per economic activity in the EU and per energy-intensive manufacturing sector – 2021 (%)



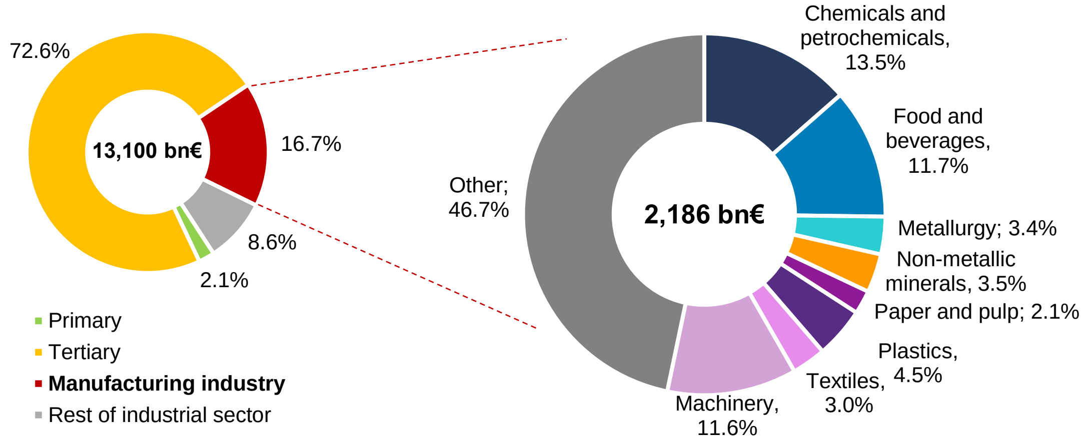
Key takeaways

- **The year 2021 provides insights into the structure of GHG emissions in Europe before the peak of the energy crisis that followed Russia's invasion of Ukraine.**
- **In 2021, manufacturing industries represented around 27% of EU GHG emissions.**
- **The chemicals and petrochemicals, metallurgy and non-metallic minerals sectors accounted for 80% of the manufacturing industries' emissions – mostly due to feedstocks and emissions associated with the processes.**
- **Other large sectors in terms of GHG emissions included food and beverages – due to the size of the industry as exemplified by its share of Gross Value Added (GVA) and employment (see next slide) – as well as paper and pulp.**

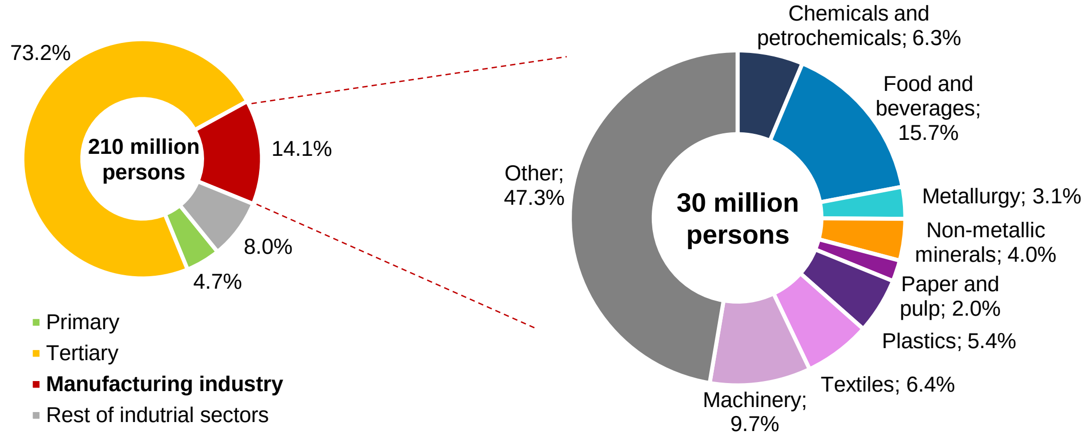
Source: Compass Lexecon analysis based on Eurostat data.
Note: The Greenhouse gases (GHG) emissions considered includes CO2, N2O in CO2 equivalent, CH4 in CO2 equivalent, HFC in CO2 equivalent, PFC in CO2 equivalent, SF6 in CO2 equivalent, NF3 in CO2 equivalent, thus it differs from the scope of the EU ETS.
Note: Non-metallic minerals include cement, glass and ceramics. Metallurgy includes iron and steel and non-ferrous metals such as aluminium and copper. Others includes manufacture of wood, fabricated metal products, electronics, electrical equipment, transport equipment and furniture, and printing and reproduction of recorded media. Rest of the industry includes electricity, gas, steam and air conditioning supply; water supply including sewerage, waste management and remediation activities and construction activities.

Manufacturing industries accounted for 17% of the Gross Value Added produced in the EU and employed 14% of the EU's workforce in 2021

Gross Value Added per economic activity in the EU and per energy-intensive manufacturing sector – 2021 (%)



Total employment per economic activity in the EU and per energy-intensive manufacturing sector – 2021 (%)



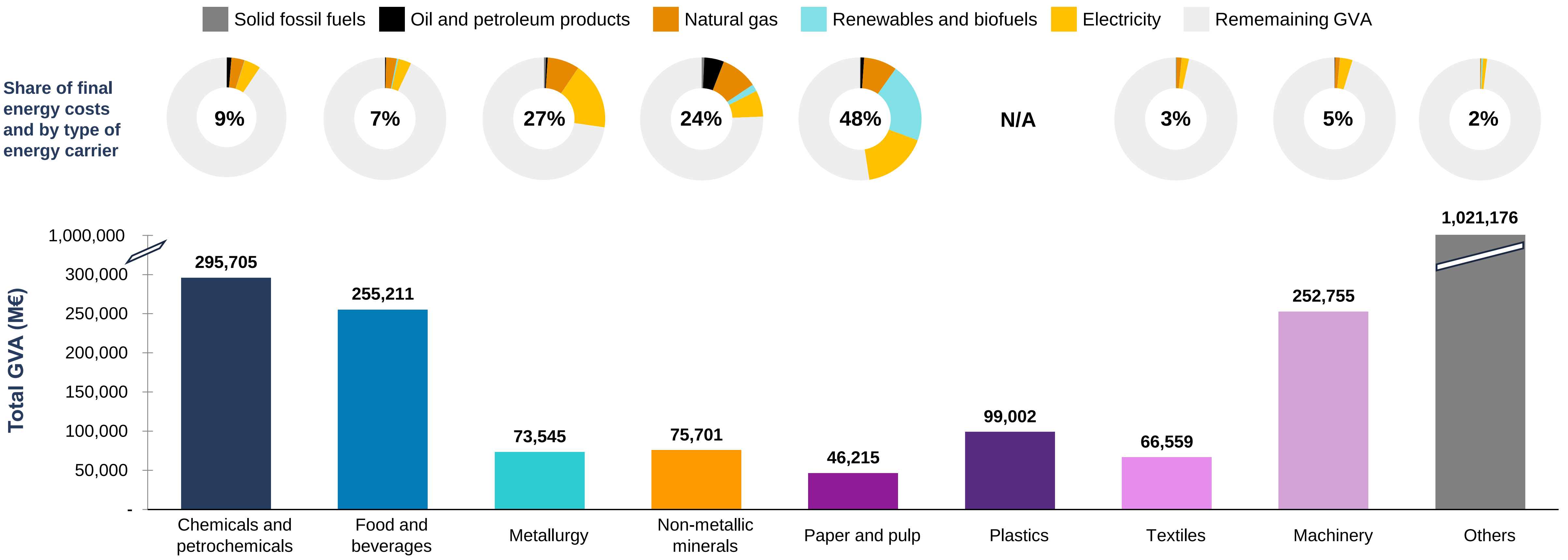
Key takeaways

- **In 2021, manufacturing industries represented around 17% of the GVA created in the EU and employed 14% of the workforce.**
- **The three largest emitting sectors – chemicals and petrochemicals, metallurgy and non-metallic minerals – accounted for around 20% of the manufacturing industries' GVA and employed around 13% of the EU workforce. The food and beverages sector was associated with a GVA contribution of almost 12% and employed almost 16% of the workforce.**
- **In addition, most manufacturing industries are subject to high levels of international trade as well as being key to downstream sectors of the economy.**

Source: Compass Lexecon analysis based on Eurostat data.
Note: The Gross Value Added is a measure of the value of goods and services produced, adjusted for the cost of inputs and raw materials (intermediate consumption). It differs from the Gross Domestic Product as it integrates directly the intermediate consumption and does not consider taxes and subsidies. It's widely used for understanding the contribution of different sectors to the economy as it provides a more granular view of economic performances (see here).
Note: Non-metallic minerals include cement, glass and ceramics. Metallurgy includes iron and steel and non-ferrous metals such as aluminium and copper. Others includes manufacture of wood, fabricated metal products, electronics, electrical equipment, transport equipment and furniture, and printing and reproduction of recorded media. Rest of the industry includes electricity, gas, steam and air conditioning supply; water supply including sewerage, waste management and remediation activities and construction activities.

Energy costs were equivalent to a relatively large share of the GVA for the paper and pulp, the metallurgy and the non-metallic minerals sectors in 2021

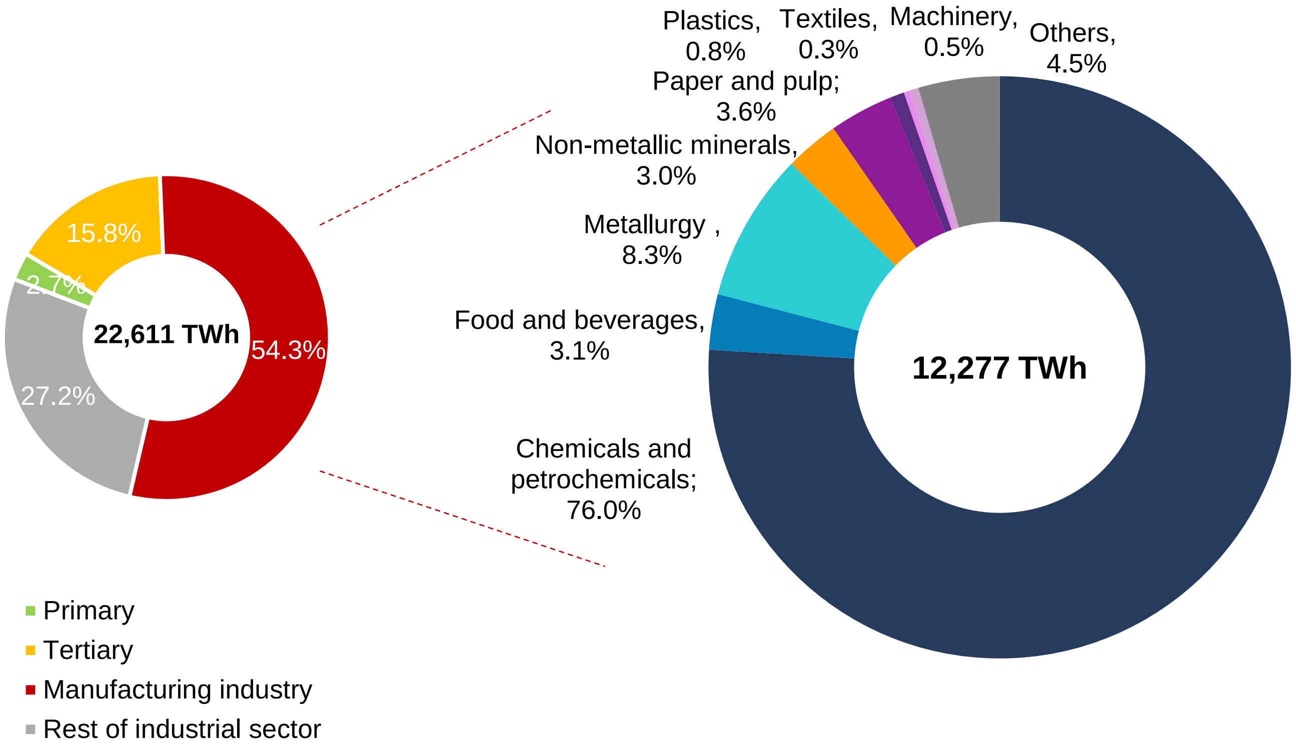
Total GVA and share of final energy cost per energy-intensive manufacturing sector – 2021 (M€)



Source: Compass Lexecon analysis based on Eurostat data; EnergyMarketPrice.
Note: No information was available for the plastics sector on energy consumption per energy carrier.
Note: Energy costs were computed as the multiplication of the energy consumption per energy carrier with the corresponding prices: namely, Solid fossil fuels price corresponds to the 2021 average coal price (lignite), Oil and petroleum products price corresponds to the 2021 average Brent spot, Natural gas price corresponds to the 2021 average price of the TTF spot, Renewables and biofuels price corresponds to the 2021 average European softwood price, and Electricity price corresponds to the 2021 average industrial European electricity tariffs (excluding taxes).

Manufacturing industries generated more than 50% of the total primary energy demand in the EU in 2021, with chemicals accounting for over 75% of this demand

Total energy used per economic activity in the EU and per energy-intensive manufacturing sector – 2021 (%)



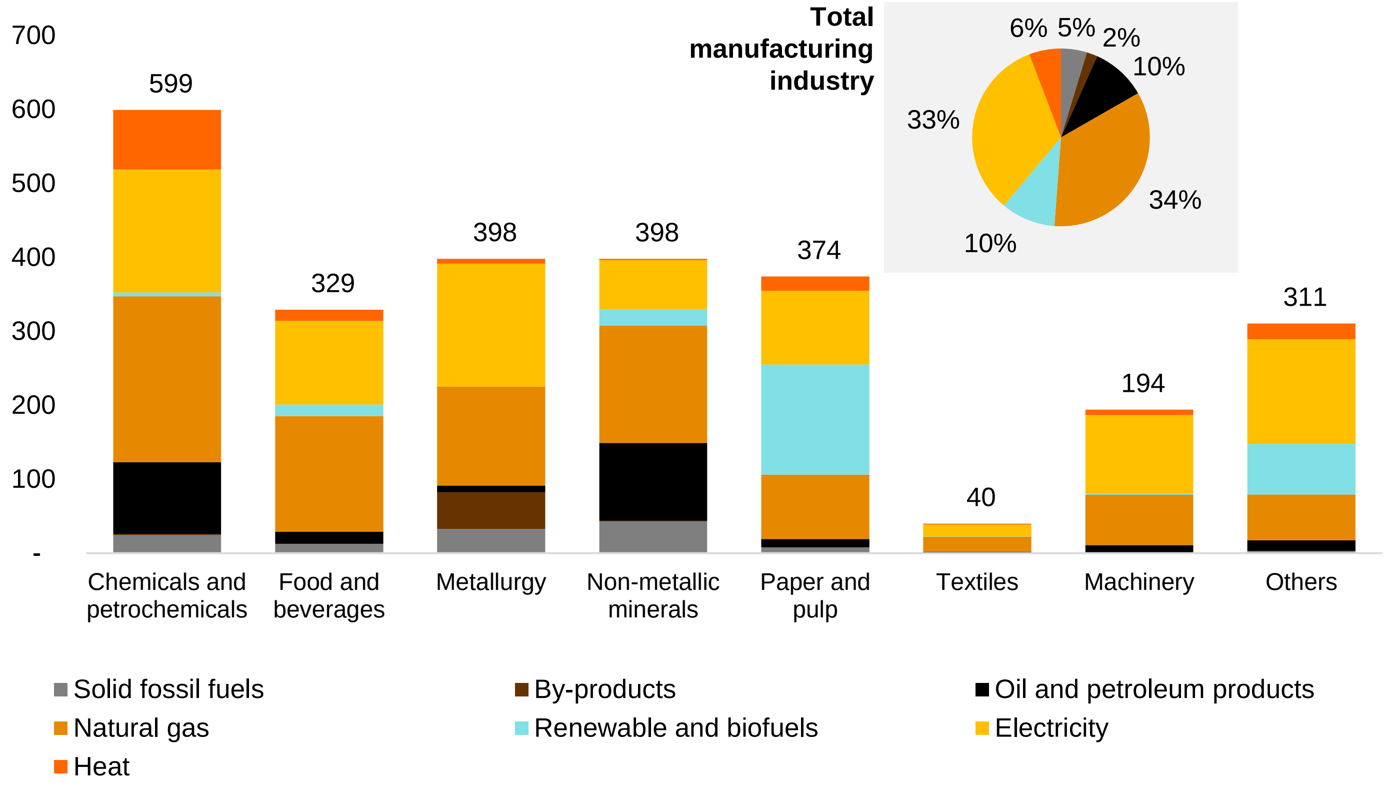
Key takeaways

- The year 2021 provides insights into the structure of primary energy consumption in Europe before the peak of the energy crisis that followed Russia's invasion of Ukraine.
- Despite relatively smaller shares of GVA and employment as compared to other sectors of the economy, manufacturing industries accounted for over half of the entire energy used in the EU in 2021, illustrating their high energy intensity.
- The chemicals and petrochemicals sector represented over 75% of energy used in manufacturing sectors – primarily due to feedstocks.
- The metallurgy, non-metallics minerals, food and beverages and paper and pulp sectors accounted between 3% and 8% each of the energy used in manufacturing industries.

Source: Compass Lexecon analysis based on Eurostat data.
Note: Total energy used includes both transformation and end-uses.
Note: Non-metallic minerals include cement, glass and ceramics. Metallurgy includes iron and steel and non-ferrous metals such as aluminium and copper. Others includes manufacture of wood, fabricated metal products, electronics, electrical equipment, transport equipment and furniture, and printing and reproduction of recorded media. Rest of the industry includes electricity, gas, steam and air conditioning supply; water supply including sewerage, waste management and remediation activities and construction activities.

Over half of the final energy consumption in manufacturing industries still relied on fossil fuels in 2021 – however, some industrial processes are already electrified

Final energy consumption per energy carrier in each energy-intensive manufacturing sector for energy uses (excluding feedstock) – 2021 (TWh)



Key takeaways

- Natural gas and electricity already supplied over two-thirds of final energy consumption for energy usage – excluding feedstock – in 2021 for EU manufacturing industries.
- Electricity is already the source for over 30% of the energy consumption of EU manufacturing industries, partly due to processes being already electrified (e.g., production chains, machinery, electric furnaces, etc.) and partly for other uses such as lighting and IT technologies.
- Renewable energy - mainly biomass - is widely used in the paper and pulp sector, as renewable waste products are derived from the production processes of the final products.
- Fossil-based energy sources are still used for high-temperatures processes, notably in the metallurgy (e.g., steel production) and non-metallic minerals (e.g., cement) sectors.

Source: Compass Lexecon analysis based on Eurostat data.
Note: No information was available for the plastics sector on energy consumption per energy carrier.
Note: Non-metallic minerals include cement, glass and ceramics. Metallurgy includes iron and steel and non-ferrous metals such as aluminium and copper. Others includes manufacture of wood, fabricated metal products, electronics, electrical equipment, transport equipment and furniture, and printing and reproduction of recorded media. Rest of the industry includes electricity, gas, steam and air conditioning supply; water supply including sewerage, waste management and remediation activities and construction activities.

All manufacturing industrial sectors have at least one highly trade-intensive sub-sector, according to the carbon leakage mitigation methodology of the EU

- A sector's trade intensity measures its exposure to international trade and the associated competitive pressure. A high trade intensity of **above 10%** signifies that the sector is at risk of carbon leakage – this is the case for all manufacturing industrial sectors except cement.
- The carbon leakage indicator of a sector is the product of the trade intensity and the emission intensity. Sectors with a carbon leakage indicator **exceeding 0.2** shall be deemed to be at risk of carbon leakage – this is the case for all manufacturing industrial sectors except food and beverages, plastics and low-temperature chemicals.

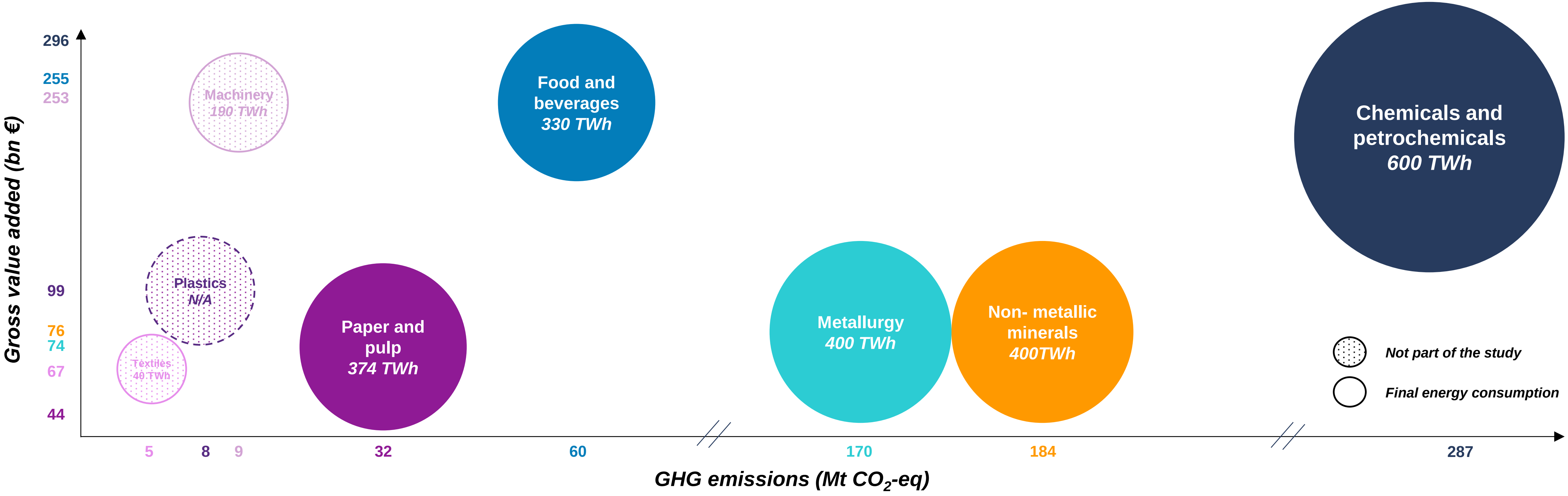
Manufacturing industrial sectors considered	Sub-sectors considered	Trade intensity Sector average (%)	Emission intensity Sector average (kg CO_2/€)	Carbon leakage indicator Sector average
		A	*B*	*A x B*
Chemicals and petrochemicals (high-temperature)	▪ Manufacture of basic pharmaceutical products & pharmaceutical preparations ▪ Manufacture of high temperature chemicals and chemical products (industrial gases, fertiliser, (in)organic basic chemicals, fibre)	43%	2.57	1.09
Cement	▪ Manufacture of cement	5%	4.97	0.23
Aluminium	▪ Manufacture of aluminium	35%	4.63	1.63
Glass	▪ Manufacture of glass	26%	1.78	0.46
Other Non-metallic minerals	▪ Manufacture of other non-metallic minerals (ceramics, lime, plaster, stones etc.)	27%	2.09	0.56
Other non-ferrous metals	▪ Manufacture of other basic metals (precious metals, copper, lead, zinc, etc.)	50%	1.07	0.54
Iron and steel (Metallurgy)	▪ Manufacture of iron and steel	26%	5.56	1.45
Paper and pulp	▪ Manufacture of paper and paper products	20%	1.46	0.29
Food and beverages	▪ Manufacture of food products ▪ Manufacture of beverages	17%	0.32	0.05
Plastics	▪ Manufacture of rubber and plastic products	28%	0.41	0.11
Chemicals and petrochemicals (low-temperature)	▪ Manufacture of coke and refined petroleum products ▪ Manufacture of low temperature chemicals and chemical products (pesticides, paints, soap, perfumes, glues, etc.)	69%	0.12	0.08
Others	▪ Others manufacturing industries	47%	0.08	0.04

Source: Compass Lexecon analysis based on EU's Carbon Leakage Regulation
Note: The sub-sectors considered here are based on the EU's NACE 2 codes. For further details, please refer to the appendix.
Note: Trade intensity is calculated as the sum of imports and exports divided by the sum of turnover and imports; the average of each sector was weighted by the value of each sub-sector application. Emission intensity is the sum of the direct and indirect emission intensity (DEI and IEI) in kg CO_2/€, with the DEI (IEI) being the ratio between direct (indirect) emissions and the GVA entire sector's direct (indirect) emissions, the average of each sector was weighted by the value of each sub-sector application. The carbon leakage indicator is the product of the trade intensity and the emission intensity.

The study focuses on the manufacturing sectors associated with the most GHG emissions as well as final energy consumption

- The chemicals and petrochemicals, non-metallic minerals, metallurgy, food and beverages and paper and pulp sectors are the manufacturing sectors responsible for the highest share of emissions as well as a large share of the final energy consumption, while representing major contributors to GVA of manufacturing industries.

Manufacturing sector distribution per GHG emissions, Gross value added and Final energy consumption *(representation not at scale)*



Source: Compass Lexecon analysis based on Eurostat data.
Note: No information was available for the plastics sector on energy consumption per energy carrier.

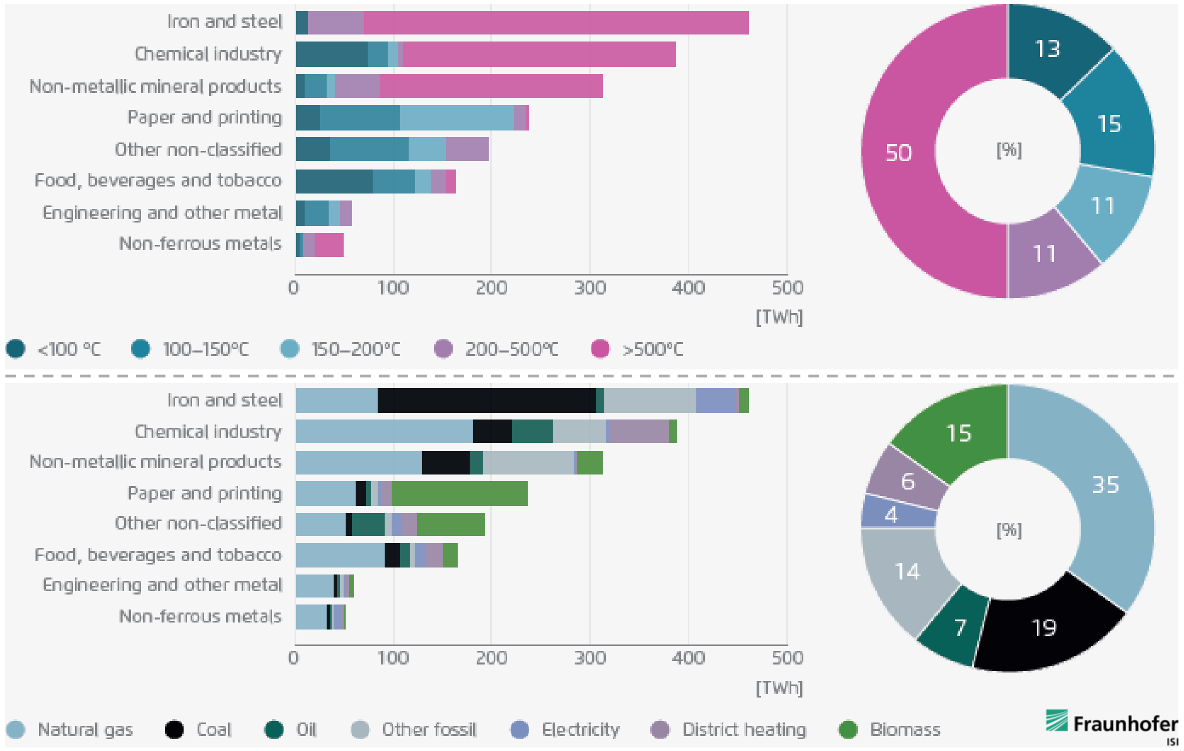
2.2 Technical potential of electrification in EU manufacturing industries

Process heating is the largest source of energy consumption in manufacturing industries – the study focuses on the direct and indirect electrification of these applications

Process heating accounts for 60% of the manufacturing industries' total energy demand, with half of that demand linked to high-temperature processes (above 500°C).

- Process heating applications in manufacturing industries have been relying on fossil fuel consumption for 75% of the demand, driven by the temperature level and energy density requirements of the raw material industries.
- The iron and steel, chemicals and non-metallic minerals sectors represent the bulk of industrial energy demand for process heating.
- Existing technological systems such as large furnaces and kilns meet the current need for high temperatures and energy density by relying on fossil fuels – mainly natural gas and coal.
- Sectors with lower temperature requirements for process heat have also historically been relying on fossil fuels. For instance, natural gas represents the majority of the energy demand in the food and beverages sector.
- Process heat could be delivered through either direct or indirect electrification, depending on the range of available and suitable technologies per industrial sector and application.

Final energy demand for process heating of different manufacturing industrial sectors, per temperature range and energy carrier – 2019 (TWh, %)



Source: Fraunhofer ISI(2024), Direct electrification of industrial process heat

Source: Compass Lexecon analysis based on Fraunhofer ISI's Direct electrification of industrial process heat study (2024).

A range of low-carbon technologies are identified as potential options for the direct electrification of heat in manufacturing industries

- While some direct electrification technologies are readily available and can be widely used as of today, such as heat pumps and electric boilers, other technologies are expected to have a relevant role in the decarbonisation of industrial processes in the medium- and long- term, such as resistance heating and EAFs.

Focus of the analysis

	Description	Capacity	T°	Sectors	Potential application
Industrial heat pumps	An industrial heat pump absorbs low-temperature heat from a source (air, water, or ground) and uses a refrigeration cycle (compressor, evaporator, condenser) to raise the temperature for industrial heating or cooling. They have very high efficiencies compared to conventional heating.	100MW	250°C	▪ Food ▪ Paper ▪ (Petro)chemicals	▪ Milk powder production ▪ Paper drying ▪ chemical park vapour supply
Electric Boilers	An electric boiler uses resistive heating elements to convert electrical energy into thermal energy, heating water or producing steam for industrial or heating applications.	75MW	500°C	▪ Food ▪ Paper ▪ (Petro)chemicals	▪ Milk powder production ▪ Paper drying ▪ Chemical park vapour supply
Resistance heating	Resistance heating generates heat by passing electric current through a resistive material (such as a metal wire or strip), which converts electrical energy into heat due to the material's resistance. It offers precise temperature control, rapid heating and low maintenance.	80kW/m²	1850°C	▪ All	▪ Melting of cast iron ▪ Melting of flat glass ▪ Melting of plastics
Induction heating	Induction heating produces heat in conductive materials (metals) by inducing eddy currents using a rapidly alternating magnetic field, causing resistive heating in the material itself.	42MW	3000°C	▪ Metals	▪ Heating of flat/long steel ▪ Melting of cast iron ▪ Melting of flat glass ▪ Heating of aluminium
Plasma torches	Plasma torches ionise a gas (like air or argon) by passing it through a high-voltage electric arc, creating plasma that can reach extremely high temperatures for cutting or treating materials.	8MW	5000°C	▪ Minerals	▪ Cement clinker burning ▪ Metal cutting
Electric arc furnaces (EAFs)	EAF melts steel or other metals by forming electric arcs between electrodes and the metal charge, where the intense heat generated by the arc melts the material through direct exposure.	200MW	1800°C	▪ Metals	▪ Secondary steel production
Shock-wave heating	Shock-wave heating uses high-pressure waves to rapidly heat materials by passing them through rotating cascades of blades, where sudden compression generates intense heat in the fluid due to the rapid pressure increase. However, the technology is still in development and its future progress is uncertain.	1MW	700°C	▪ Minerals	▪ Cement clinker burning ▪ Specialized industrial processes
Direct electrolysis	Direct electrolysis is an electrochemical process that involves splitting a compound into its basic elements using an electric current. It can be applied to a wide range of materials but shows great potential in metallurgies as it enable the extraction or transformation of element without the use of reducing agents.	N/A	5000°C	▪ Metals	▪ Primary steel production

Source: Compass Lexecon analysis based on Fraunhofer ISI's Direct electrification of industrial process heat study (2024).
Note: Plasma torches and shock-wave heating were kept out of scope due to high CAPEX costs and lack of maturity.

Most industrial processes are estimated to have at least one direct electrification solution technically available as a low-carbon technology at scale by 2040

- Direct electrification technologies – heat pumps and electric boilers – are already mature and available for low-temperature industrial processes.
- Technologies for higher temperature processes – such as resistance heating and EAFs – are expected to become more available within the next decade; however, some high-temperature processes could still face challenges regarding the availability of suitable low-carbon technologies at scale before 2040.

Direct electrification low-carbon technologies for a subset of industrial application and their potential readiness

Sector	Industrial application	Heat pumps	Electric boilers	Resistance heating	Induction heating	Plasma torches	Electric arc furnaces (EAFs)	Stock-wave heating	Direct electrolysis
Food and beverages	Steam generation	2025	2025						
Paper and pulp	Steam generation	2025	2025						
	Direct heating			2035	2035				
Plastics	Steam generation	2025	2025						
Chemicals and petrochemicals	Steam cracking			2030				2030	
	Steam reforming			2030				2030	
	Carbon black			2035				2035	
Metallurgy	Primary steel								2040+
	Secondary steel						2025		
	Hot rolled steel			2035	2035	2035		2035	
	Oxygen steel						2040+		
	Primary aluminium			2035					
	Secondary aluminium			2035					
	Non-ferrous metals			2025					
Non-metallic minerals	Container glass			2025		2035		2035	
	Flat glass			2040+					
	Cement clinker			2035 / 2040+					
	Lime			2030 / 2035					
	Ceramic			2035		2035		2035	

Technological readiness: 2025 | 2030 | 2035 | 2040+

Source: Compass Lexecon analysis based on Fraunhofer ISI's Direct electrification of industrial process heat study (2024); Germany's Federal Environment Agency's CO2-neutral process heat generation study (2023).
Note: Cement clinker production could be partially electrified (calcination step) by 2035. The electrification of lime production could vary between 2030 and 2035 according to the industrial process.

Indirect electrification low-carbon technologies are also expected to provide additional options for decarbonisation in manufacturing industries

- While indirect electrification technologies could constitute alternative solutions to direct electrification technologies in some industrial processes, they might be the most technically suitable solution in other processes which are associated with specific requirements that make direct electrification challenging.
- Hybrid systems, combining electric and fuel-based heating, could serve as a temporary solution in the transition to industrial decarbonisation.

Focus of the analysis

	Description	T°	Sectors	Potential application
Hydrogen	Hydrogen boilers are commercially available as industrial steam boilers and with technical characteristics comparable to natural gas boilers (e.g., similar temperature ranges, steam capacity load requirements, etc.).	100-400°C	▪ Food ▪ Paper ▪ (Petro)chemicals	▪ Milk powder production ▪ Paper drying ▪ chemical park vapour supply
Hydrogen	Hydrogen heating consists of retrofitting the existing infrastructures (burners, fuel lines, etc.) to switch from natural gas to hydrogen. Hydrogen heating processes thus vary greatly depending on the industrial application/plant.	>1700°C	▪ Metallurgy ▪ Minerals	▪ Heating of flat/long steel ▪ Melting of cast iron ▪ Heating of aluminium ▪ Melting of flat glass ▪ Firing of cement clinker
Hybrid processes	A hybrid system can combine electrical and fuel-based heating and or thermal heating as well as storage solutions in one system (centralised process). This includes heat-pump solutions.	90-400°C	▪ Food ▪ Paper ▪ (Petro)chemicals	▪ Milk powder production ▪ Paper drying ▪ chemical park vapour supply
Hybrid processes	A hybrid process can split the heating process between different systems (decentralized process). The heat sources intervene at different phases of the industrial process, allowing the advantages of each source to be exploited.	100-1850°C	▪ Metallurgy ▪ Minerals	▪ Heating of flat/long steel ▪ Melting of cast iron ▪ Melting of flat glass ▪ Firing of cement clinker
Biomass	Biomass heating, considered CO_2-neutral, refers to organic materials used as solid, liquid, or gaseous energy sources. Its use in process heating is limited to specific industrial applications. Thus, we do not consider biomass in our analysis.	140-1500˚C	▪ Paper ▪ Metals ▪ Minerals	▪ Paper drying ▪ Melting of flat glass ▪ Firing of cement clinker
Power-to-liquid	Power-to-liquid (PtL) involves producing liquid fuels from renewable electricity, hydrogen, and carbon dioxide. However, PtL use is targeted at the transport and aviation sectors and the use of liquid fuels (oil) for process heating is very limited in Europe. Thus, we do not consider PtL in our analysis.	N/A	N/A	N/A
Power-to-methane	Methanation is the process of producing methane from hydrogen, it does not require any conversion but still emits CO_2 and is expensive to produce. Thus, we do not consider methanation in our analysis.	N/A	N/A	N/A

Source: Compass Lexecon analysis based on Germany's Federal Environment Agency's CO2-neutral process heat generation study (2023).
Note: Biomass has not been included in the scope of the analysis despite being a mature solution, because it is mainly exploited locally, resulting in a lack of organised trade and a lack of information on its availability.
Note: Hybrid systems, such as one based on indirect electrical resistance heating coupled to a natural gas furnace, are developed to answer high process temperatures and high production capacities.
Note: According to forecasts (Kreidelmeyer et al. (2020)), the prices of methane from renewable sources are not expected to be competitive in the future, as the costs of synthetically produced green methane are approximately 50 % higher than the costs of green hydrogen.

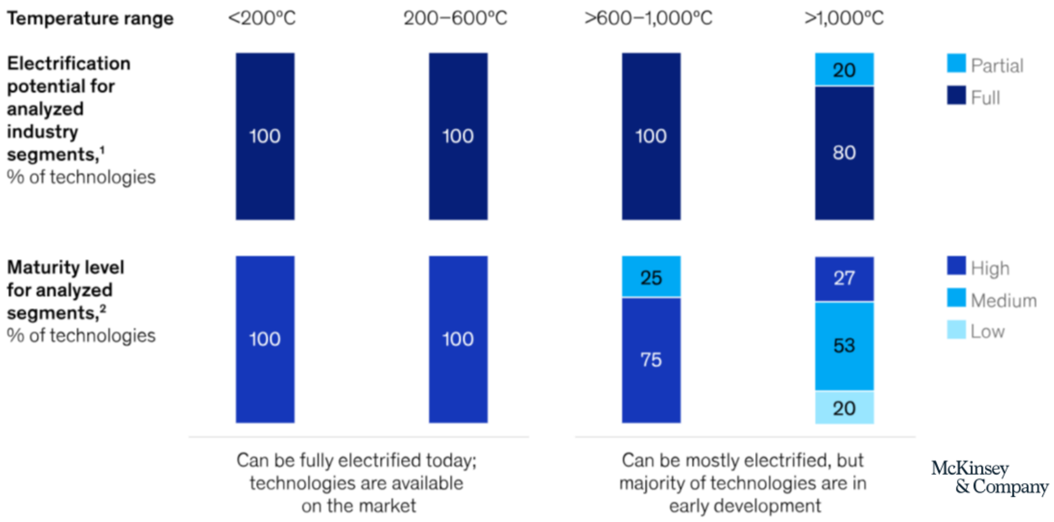
Several studies show that the technical electrification potential of industrial processes in manufacturing industries could reach between 90% to 99% in the mid-2030’s

Methodology

- We have analysed different studies analysing the potential of low-carbon technologies to decarbonize industrial heating process and their respective technical maturities.
- We have identified key messages in our review common to all the studies:

1. **Low-to-medium temperature (100°C – 500°C) industrial heating processes can already be electrified with commercially mature and competitive low-carbon technologies – specifically in the food and beverages, paper and pulp and chemical sectors.**
2. **Currently, 50% to 70% of all industrial heating processes have an alternative low-carbon technology that could technically decarbonise energy usage.**
3. **In 2035, 90% to 99% of industrial heating processes are expected to have a mature low-carbon technology available to enable their decarbonisation.**

Electrification potential and maturity level by temperature range



[1]For full potential, all fuels conventionally used can be substituted for electricity-based technologies; partial potential requires hybrid systems.
[2]Low maturity technologies are in the R&D or prototype phase, medium maturity are pilot projects, and high maturity have suppliers available on the market.

Source: McKinsey & Company (2024), Net-zero electrical heat: A turning point in feasibility

“In Europe, the switch to electric industrial heating should accelerate considerably in the coming years due to technological development”

Source: Boston Consulting Group(2024), Transformation Paths for Germany as an Industrialised Nation

Source: Compass Lexecon analysis based on Fraunhofer ISI’s Direct electrification of industrial process heat study (2024); Boston Consulting Group’s Transformation Paths for Germany as an Industrialised Nation study (2024); McKinsey & Company’s article on Net-zero electrical heat: A turning point in feasibility (2024); Madeddu et al.’s paper on The CO2 reduction potential for the European industry via direct electrification of heat supply (2020).
Note: Fraunhofer ISI’s study and Madeddu et al.’s paper presented a thorough review of alternative process heating technologies per industrial sector and per key process heating applications with the sector or its sub-sectors. BCG’s study looks at investments in heat pumps, electric heat generators, industrial power-to-heat systems and heat storage systems. McKinsey and Company’s article evaluated 60 industrial processes across eight sectors (metals and mining, cement, chemicals, fertilisers, paper and pulp, construction materials, food and beverages, and machinery and equipment) as well as 13 types of industrial technologies.

2.3 Economic potential of electrification in EU manufacturing industries

We assess the conditions for the competitiveness of low-carbon process heating solutions as compared to incumbent fossil-based technologies

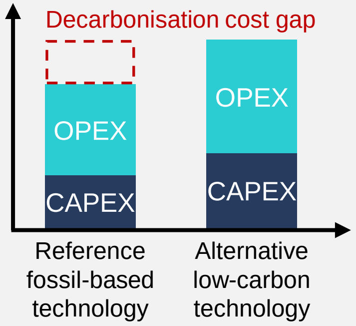
The study aims at estimating the costs per ton of product of different low-carbon technologies for different industrial applications through a simple bottom-up model of energy production costs.

Key assumptions:[1]

- CAPEX costs are based on estimates for a new-build investment based on reference estimates from public sources and were cross-checked with industry representatives during the stakeholder consultation process.
- Additional costs for system integration – required infrastructure upgrades to accommodate the low-carbon technology – are added as a share of CAPEX.
- The total cost is the average over 2025-2045 but assumes no free allocations (considering they are phased-out for most of the operating period).

Key output: the decarbonisation cost gap

- Decarbonisation cost gap – difference in costs between the existing fossil-based technology and the alternative low-carbon solution.
- Repartition of costs between CAPEX and OPEX.
- Tipping points for energy/carbon prices at which low-carbon solutions reach cost parity with the reference fossil-based technology.



Limitations of the analysis:

- The models offer a simplified representation of the different cost components (CAPEX, OPEX, others) associated with low-carbon technologies available for a selected application within a given industry aimed at capturing the average cost gap between competing solutions over the assumed economic life of the process (15 to 30 years).
- The model is based on the 2025-2045 period but does not account for:
  - CAPEX uncertainty and variability over time and per region.
  - Energy price uncertainty and variability over time and per region.
  - Practical challenges and differentiated risks per region.
  - The availability and maturity of the technology as of 2025.
  - Free allowances under the EU ETS, possible subsidies and/or possible revenue streams from demand-side response participation in energy markets.
- A set of sensitivity analyses was carried out to identify decarbonisation cost gaps, tipping points based on electricity prices, green hydrogen prices, EU ETS allowance prices and possible investment aid as share of CAPEX.

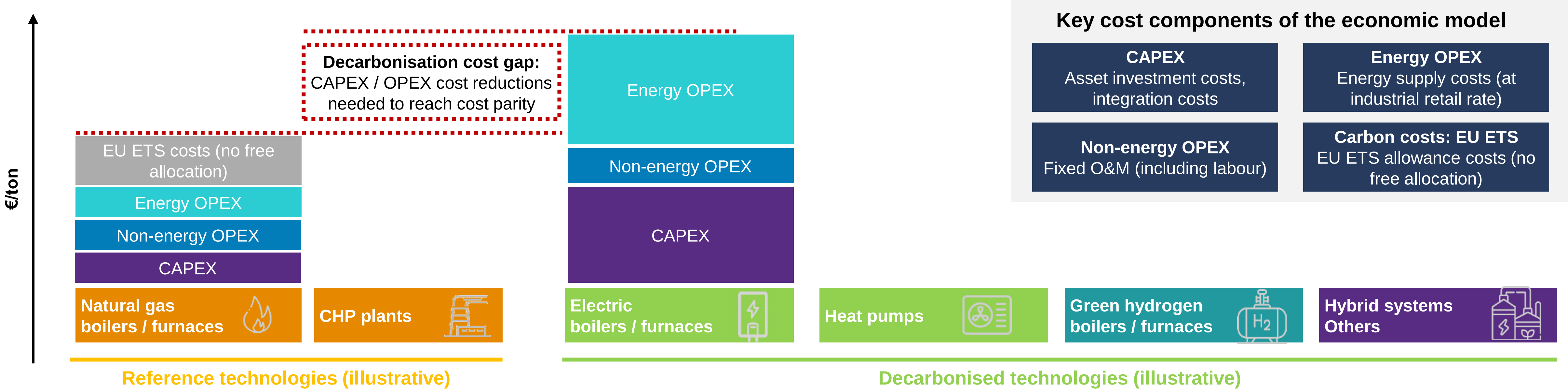
Source: Compass Lexecon analysis; [1] data from Germany's Federal Environment Agency's CO2-neutral process heat generation study (2023); Fraunhofer ISI's Direct electrification of industrial process heat study (2024); EC's 2040 Climate Target Impact Assessment (2024).
Note: We acknowledge that the business case of incumbent fossil-based technologies used in industrial processes can be considered as already depreciated compared to international competition. However, as a first step, we focus the study on the comparison between fossil and low-carbon technologies for production in the EU considering the incumbent technologies as reference to pin down economic incentives to decarbonise domestically.

We selected seven industrial applications for which we model energy production costs per technology and the decarbonisation cost gap and highlight tipping points for cost parity

Industrial sectors and heating applications considered

1. Food & Beverages: Milk powder production	**2. Paper & Pulp:** Paper drying	**3. Chemicals:** Vapour supply	**4. Iron & Steel:** Heating Flat/long steel	**5. Aluminium:** Alumina digestion	**6. Glass:** Flat glass melting	**7. Cement industry:** Cement clinker burning

Energy production costs per ton of product (€/ton)



Source: Compass Lexecon analysis.
Note: In the economic assessment, the terminology 'Chemicals' is used to designate the "Chemicals and petrochemicals" industry .

The energy and CO2 prices used in our simplified model are taken as fixed average projections to compare business cases of solutions regardless of price volatility

Energy and carbon price assumptions are based on projections taken from public sources and on industrial stakeholder exchanges.

Price assumptions:

- Prices are based on reference estimates from public sources and were cross-checked with industry representatives during the stakeholder consultation process.
- Energy prices account for energy and supply costs as well as transport and storage costs and any additional grid charges and other taxes, fees and levies.
  - Natural gas energy and supply costs are expected to some extent compared to current levels; however, transport and storage costs are expected to increase due to a lower projected demand.
  - Electricity prices are in line with EC projections over the period. The possibility to sign a power purchase agreement contract for a price well below the assumed price is not considered in the general case.
  - Green hydrogen prices are expected to decrease in line with electricity price evolutions and technological progress.
- The EU ETS allowance (EUA) price is expected to increase according to EU targets and to projections from different public sources.

Initial set of input energy and carbon price assumptions (€$_{2024}$)

	2023 Average price[(1)]	*2025-2045 Average price*[(2)]
Natural gas – Industrial retail rate (€/MWh)	75	**40**
Electricity – Industrial retail rate (€/MWh)	160	**120**
Green hydrogen price (€/MWh – €/kg)	250 – 7.5	**165 – 5**
Explicit carbon price – EU ETS allowance (€/tCO2e)	85	**150**

Note: Prices include supply costs as well as transport and storage costs and any additional grid charges, other taxes and levies

Source: Compass Lexecon analysis based on (1) Eurostat data for natural gas and electricity prices, EEX Hydrix and IEA Global Hydrogen Review 2023 for green hydrogen prices and EnergyMarketPrice for EU ETS allowance prices; (2) internal projections and EC's 2040 Climate Target Impact Assessment for electricity prices, internal projections and IEA World Energy Outlook 2024 for natural gas and EU ETS allowance prices, internal projections and IEA Global Hydrogen Review 2024 for green hydrogen prices.
Note: Biomass, Waste and Lignite input prices (5-8 €/MWh) are estimated based on European Network of Transmission System Operators for Electricity (ENTSO-E)'s 2024 Ten-Year Network Development Plan (TYNDP) scenario projections.

Up to five alternative low-carbon technologies are considered for the seven selected industrial applications, in addition to the reference incumbent fossil-based technology

- The maturity of proposed low-carbon technologies per application vary – each selected application is expected to have at least one technologically-ready solution by 2030. For all applications except for the one in the cement sector, a low-carbon technology (or relatively lower-carbon than the incumbent technology) is available.

Low-carbon technologies for the industrial sectors and heating applications considered and their potential readiness

Sector	Application	Reference	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Reference + CCS
1. Food & Beverages	Milk powder production	Natural gas (CHP plant)	Electricity (Electric boiler)	Electricity (Heat pump system)	Green hydrogen (Hydrogen boiler)		Natural gas & CCS (CHP plant with CCS unit)
2. Paper & Pulp	Paper drying	Natural gas (CHP plant)	Electricity (Electric boiler)	Electricity (Heat pump system)	Green hydrogen (Hydrogen boiler)		Natural gas & CCS (CHP plant with CCS unit)
3. Chemicals	Chemical park vapour supply	Natural gas (CHP plant)	Electricity (Electric boiler)	Electricity (Heat pump system)	Green hydrogen (Hydrogen boiler)		Natural gas & CCS (CHP plant with CCS unit)
4. Iron & Steel	Continuous heating Flat/long steel	Natural gas (Walking beam furnace)	Electricity (Crucible induction furnace)	Green hydrogen (Walking beam furnace)	Electricity & Biogas (Rotary hearth furnace)	Electricity & Green hydrogen (Rotary hearth furnace)	Natural gas & CCS (Walking beam furnace with CCS unit)
5. Aluminium	Alumina refining digestion	Natural gas (Natural gas boiler)	Electricity (Electric boiler)	Green hydrogen (Hydrogen boiler)			
6. Glass	Continuous melting of flat glass	Natural gas (Regenerative cross burner tray)	Electricity (All-electric furnace)	Green hydrogen (Regenerative cross burner tray)	Electricity & Biogas (Regenerative cross burner tray with electric boost system)	Electricity & Green hydrogen (Regenerative furnace with all-electric concepts)	Natural gas & CCS (Regenerative cross burner tray with CCS unit)
7. Cement	Continuous burning Cement clinker	Fossil fuel mix (Rotary kiln)	Electricity (Electrically-heated rotary kiln)	Green hydrogen (Rotary kiln)	Electricity & Fossil fuel mix (Rotary kiln with all-electric concepts)	Biomass & Green hydrogen & Electricity (Rotary kiln with electric boost system)	Fossil fuel mix & CCS (Rotary kiln with CCS unit)

Technological readiness 2025 | 2030 | 2035 | 2040+

Source: Compass Lexecon analysis based on Germany's Federal Environment Agency's CO2-neutral process heat generation study (2023).
Note: In the economic assessment, all above low-carbon technologies are considered regardless of their maturity level highlighted here.
Note: CCS still needs to be technologically proven and demonstrated but is considered an alternative solution in the study. In the economic assessment, the "Reference + CCS" option is faded compared to other as to not impact the results.

The competitiveness of the different low-carbon technologies to decarbonise industrial heat processes depends mostly on temperature requirements and specific constraints

Our analysis shows that industrial sectors can be classified under three categories regarding the cost competitiveness of possible low-carbon technologies. "Competitive" refers to low-carbon technology options with comparable estimated costs to the incumbent fossil-based technology in each process.

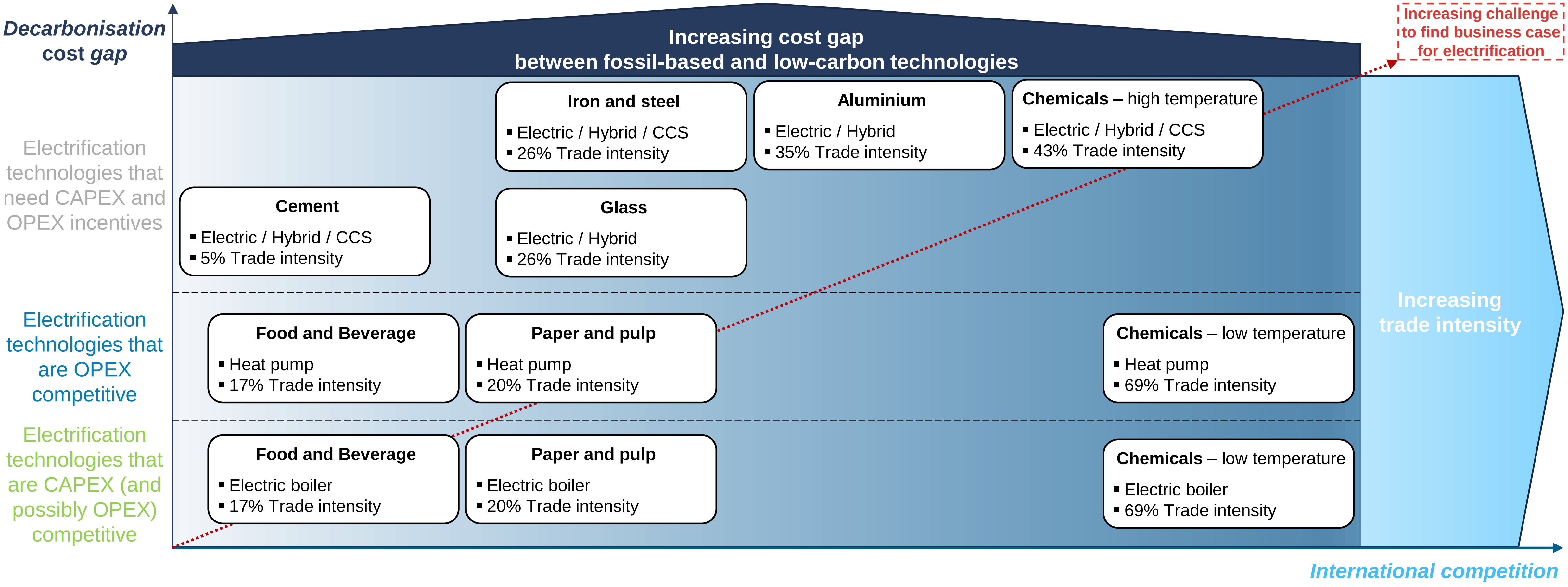
Note that our simplified analysis does not account for process-specific issues associated with sites and technologies that may affect competitiveness.

- **A** – Sectors that could decarbonise using technologies that are CAPEX (and possibly OPEX) competitive
- **B** – Sectors that could decarbonise using technologies that are OPEX competitive but require CAPEX incentives
- **C** – "Hard-to-abate" sectors with low-carbon technologies that need CAPEX and OPEX incentives

Status of incentives for decarbonisation	Process heating technologies	Industrial sectors (considered applications)			Typical approach for potential support
A – CAPEX (& OPEX) competitive	➢ Electric boilers (*with high OPEX exposure*)	➢ Food and Beverages	➢ Paper and Pulp	➢ Chemicals (low-temperature)	➢ Support to phasing-out of non-amortized carbon-intensive solutions ➢ Compensatation for interruption of production during refurbishment
B – OPEX competitive	➢ Heat pumps				➢ Phasing-out of non-amortized carbon-intensive solutions ➢ Interruption of production during refurbishment ➢ One-off CAPEX subsidies
C – CAPEX & OPEX incentives needed	➢ Electric furnaces/systems ➢ Hybrid furnaces/systems ➢ Hydrogen furnaces/systems ➢ CCS (if technologically proven)	➢ Iron and Steel (Metallurgy) ➢ Glass (Minerals)	➢ Aluminium (Non-ferrous metals) ➢ Cement (Minerals)	➢ Chemicals (high-temperature)	➢ Phasing-out of non-amortized carbon-intensive solutions ➢ Interruption of production during refurbishment ➢ One-off CAPEX subsidies ➢ Long-term OPEX rebates closing the gap

Source: Compass Lexecon analysis.
Note: The economic assessment assumes CAPEX for asset investments in 2025, with average prices over 2025-2045 of 120€/MWh for electricity, 40 €/MWh for natural gas, 165 €/MWh for green hydrogen and 150 €/tCO2e for EUAs.

Industry sectors face the greatest decarbonisation challenges when exposed to both high decarbonisation cost gaps and high international competition

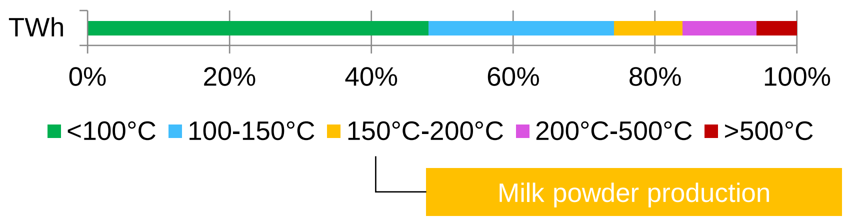


Source: Compass Lexecon analysis.
Note: International competition is evaluated through the trade intensity index which measures the exposure of specific sectors to international trade and thus the competitive pressure they face. Trade intensity is calculated as the sum of imports and exports divided by the sum of turnover and imports. For decarbonisation costs, refer to the following slides in this section.

Case study 1: Milk powder production – Economic potential for electrification

Electrification through electric boilers or heat pumps could reach cost parity with current natural gas systems in the medium-term

Food and Beverages – EU energy consumption per T°

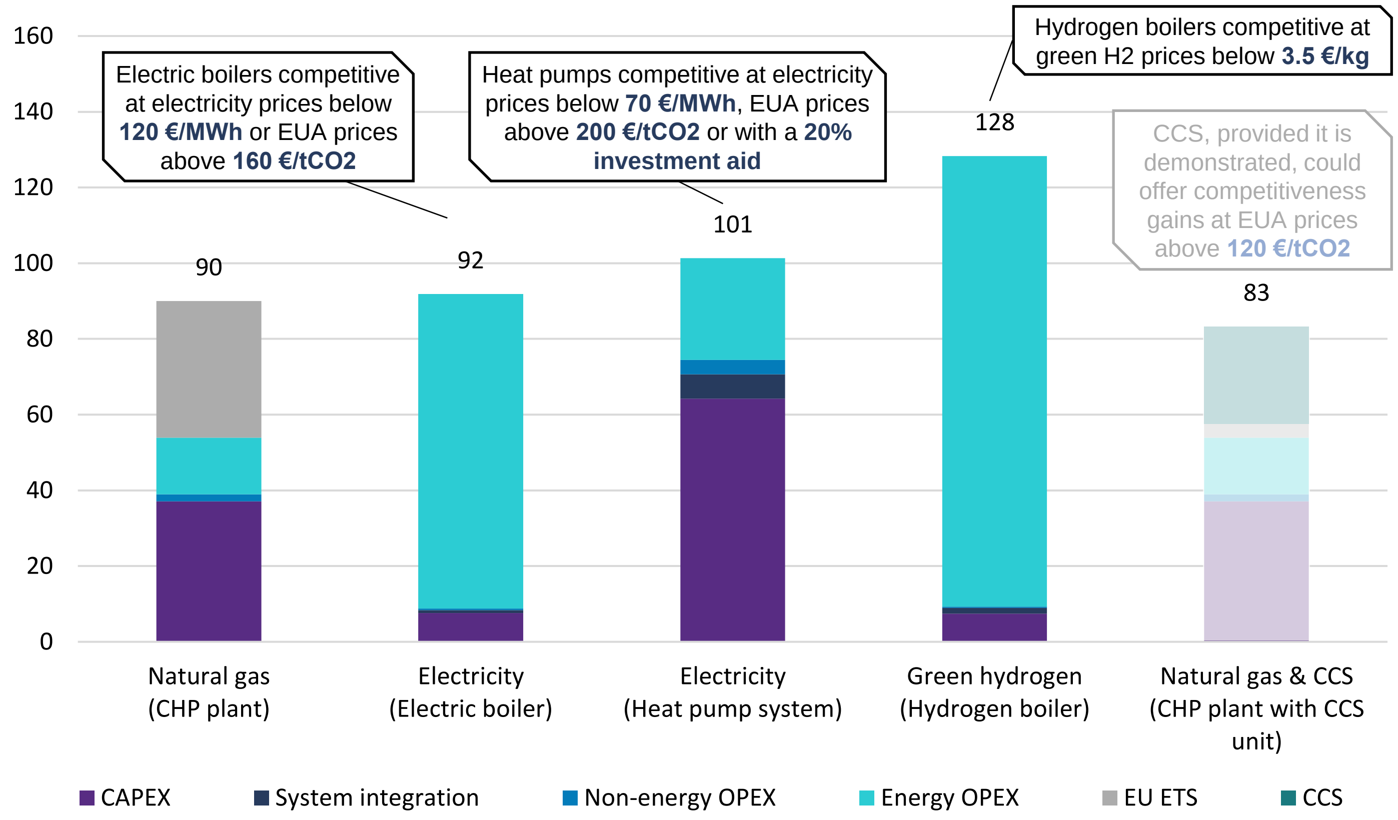


Key takeaways

A Electric boilers | B Heat pumps

- **The food and beverages sector's reliance on low-to-medium temperature processes makes the sector more prone to electrification**
- **Electric boilers are associated with low CAPEX but are fully exposed to electricity price volatility risks, while heat pumps, due to their high efficiencies, would limit exposure to price volatility and lead to energy OPEX reductions**
- **Electricity-to-gas price ratios are a key determinant in the business case and the rate of switching to electrification**
- **Green hydrogen could require lower prices to become economical, and direct electrification could be more suitable**

Energy production costs for 1 ton of steam for milk power production (€/ton)

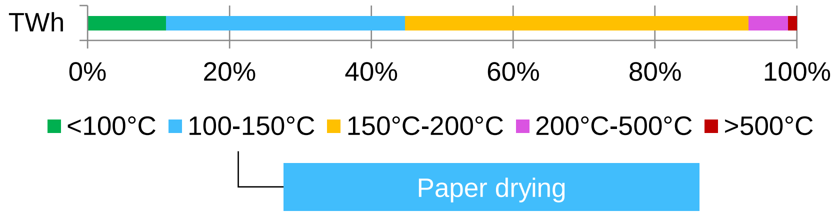


Source: Compass Lexecon analysis based on Germany's Federal Environment Agency's CO2-neutral process heat generation study (2023); Fraunhofer ISI's Direct electrification of industrial process heat study (2024); EC's 2040 Climate Target Impact Assessment (2024).
Note: In the economic assessment, no modernisation or re-investment costs are considered, EU ETS costs represent the full EUA price with no free allocations, and the generation of electricity from the CHP plant is accounted for as energy OPEX reductions. The CCS solution considered is an amine-based process with transport and storage costs also integrated (based on the Danish Energy Agency's Techno-economic assessment of CCS technologies (2024)).

Case study 2: Paper drying – Economic potential for electrification

Electrification through electric boilers or heat pumps could reach cost parity with current natural gas systems in the medium-term

Paper and Pulp – EU energy consumption per T°

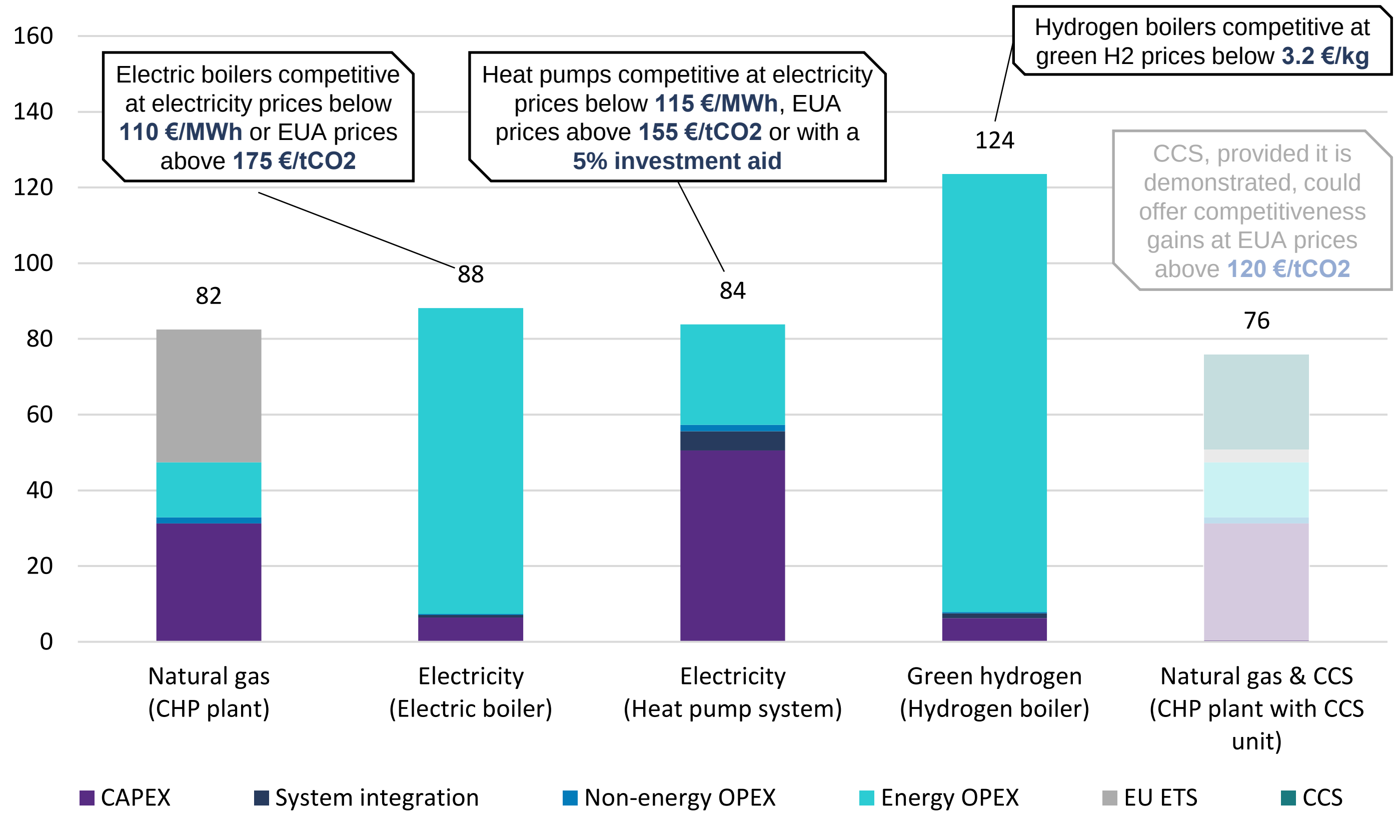


Key takeaways

(A) Electric boilers (B) Heat pumps

- The paper and pulp sector has potential for electrification, as its heating needs generally fall within the low-to-medium temperature range
- Electric boilers are associated with low CAPEX but are fully exposed to electricity price volatility risks, while heat pumps, due to their high efficiencies, would limit exposure to price volatility and lead to energy OPEX reductions
- Electricity-to-gas price ratios are a key determinant in the business case and the rate of switching to electrification
- Green hydrogen could require lower prices to become economical, and direct electrification could be more suitable

Energy production costs for 1 ton of steam used in paper drying (€/ton)

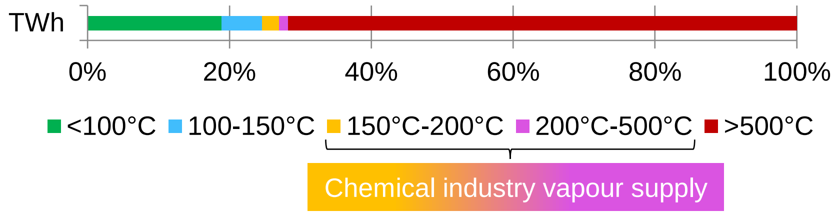


Source: Compass Lexecon analysis based on Germany's Federal Environment Agency's CO2-neutral process heat generation study (2023); Fraunhofer ISI's Direct electrification of industrial process heat study (2024); EC's 2040 Climate Target Impact Assessment (2024).
Note: In the economic assessment, no modernisation or re-investment costs are considered, EU ETS costs represent the full EUA price with no free allocations, and the generation of electricity from the CHP plant is accounted for as energy OPEX reductions. The CCS solution considered is an amine-based process with transport and storage costs also integrated (based on the Danish Energy Agency's Techno-economic assessment of CCS technologies (2024)).

Case study 3: Chemical park vapour supply – Economic potential for electrification

Electrification solutions could become on par with gas-fuelled vapour generation in the medium-term for low-to-medium temperature processes

Chemicals – EU energy consumption per T°

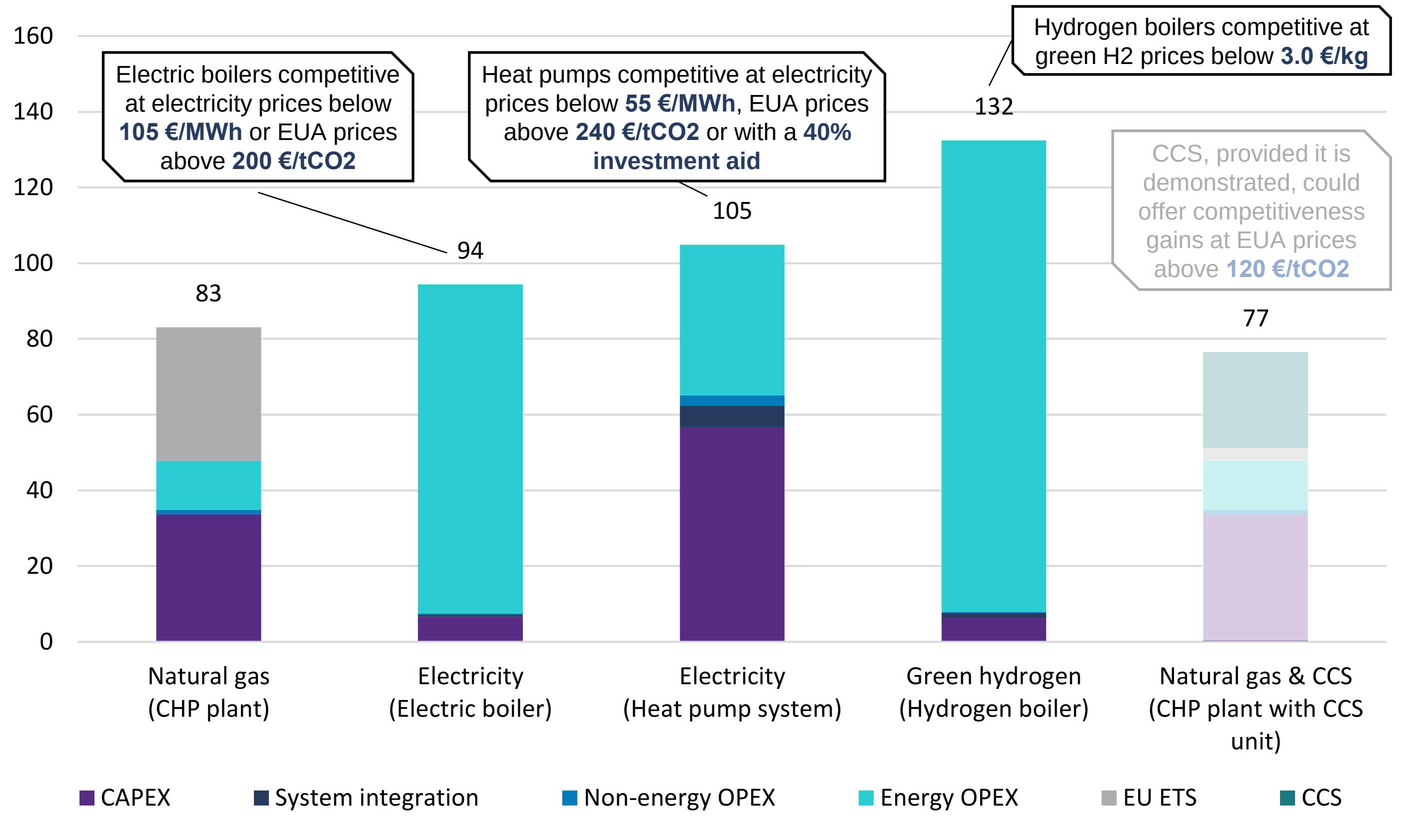


Key takeaways

Ⓐ Electric boilers Ⓑ Heat pumps

- **The chemicals industry is energy-intensive, with significant process heating requirements across a range of processes associated with mainly high temperatures**
- **Still, the electrification of low-to-medium temperature heating processes is feasible and could be envisaged**
- **Electric boilers are associated with low CAPEX but are fully exposed to electricity price volatility risks, while heat pumps, due to their high efficiencies, would limit exposure to price volatility and lead to energy OPEX reductions**
- **Green hydrogen, as well as CCS, could have a role in decarbonising processes with high temperature needs**

Energy production costs for 1 ton of chemical park vapour supply (€/ton)

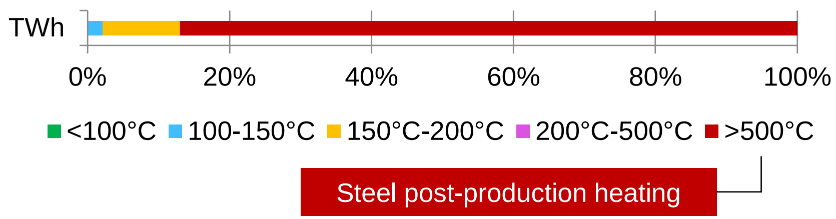


Source: Compass Lexecon analysis based on Germany's Federal Environment Agency's CO2-neutral process heat generation study (2023); Fraunhofer ISI's Direct electrification of industrial process heat study (2024); EC's 2040 Climate Target Impact Assessment (2024).
Note: In the economic assessment, no modernisation or re-investment costs are considered, EU ETS costs represent the full EUA price with no free allocations, and the generation of electricity from the CHP plant is accounted for as energy OPEX reductions. The CCS solution considered is an amine-based process with transport and storage costs also integrated (based on the Danish Energy Agency's Techno-economic assessment of CCS technologies (2024)).

Case study 4: Steel post-production heating – Economic potential for electrification

Electrification solutions are expected to face economic challenges in the medium-term, however low-carbon gas/electricity hybrid systems could serve as a temporary solution if cost parity is feasible

Iron and Steel – EU energy consumption per T°

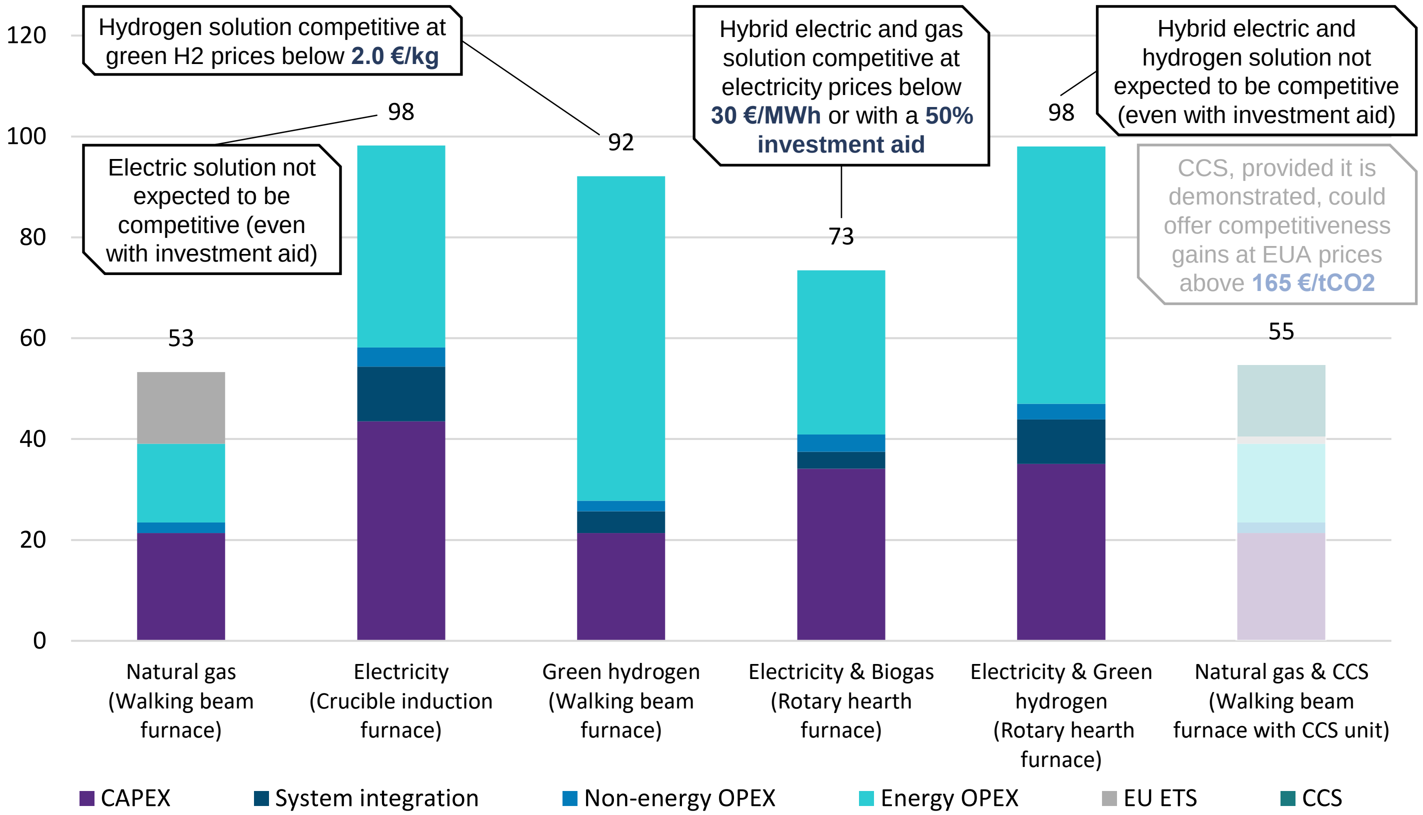


Key takeaways

Electric/hydrogen/hybrid solutions

- **The iron and steel sector is largely dependent on high-temperature processes and significant energy requirements, which are challenging to decarbonise**
- **However, steel production in the EU has partly transitioned to electrification, primarily through the use of EAFs**
- **For post-production processes, full-electric or green hydrogen-based systems are expected to still be associated with high CAPEX and/or high energy OPEX costs in the medium-term – hybrid partially-electrified systems that also rely on low-carbon natural gas could have a role to play**
- **CCS could play a key role if electric and hydrogen-based solutions still face cost and scalability issues**

Energy production costs for 1 ton of post-heated flat/long steel (€/ton)

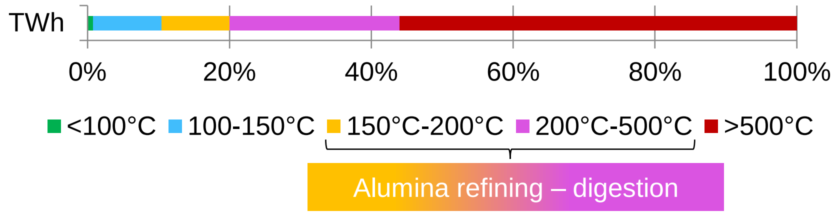


Source: Compass Lexecon analysis based on Germany's Federal Environment Agency's CO2-neutral process heat generation study (2023); Fraunhofer ISI's Direct electrification of industrial process heat study (2024); EC's 2040 Climate Target Impact Assessment (2024).
Note: In the economic assessment, no modernisation or re-investment costs are considered, and EU ETS costs represent the full EUA price with no free allocations. The CCS solution considered is a process for DRI-EAF with transport and storage costs also integrated (based on Sandbag's Steel and CCS/U study (2024) and the Danish Energy Agency's Techno-economic assessment of CCS technologies (2024)).

Case study 5: Alumina refining-digestion – Economic potential for electrification

Electrification, namely through electric boilers, still faces economic challenges associated with energy costs, which has prevented the uptake of the technology

Non-ferrous metals – EU energy consumption per T°

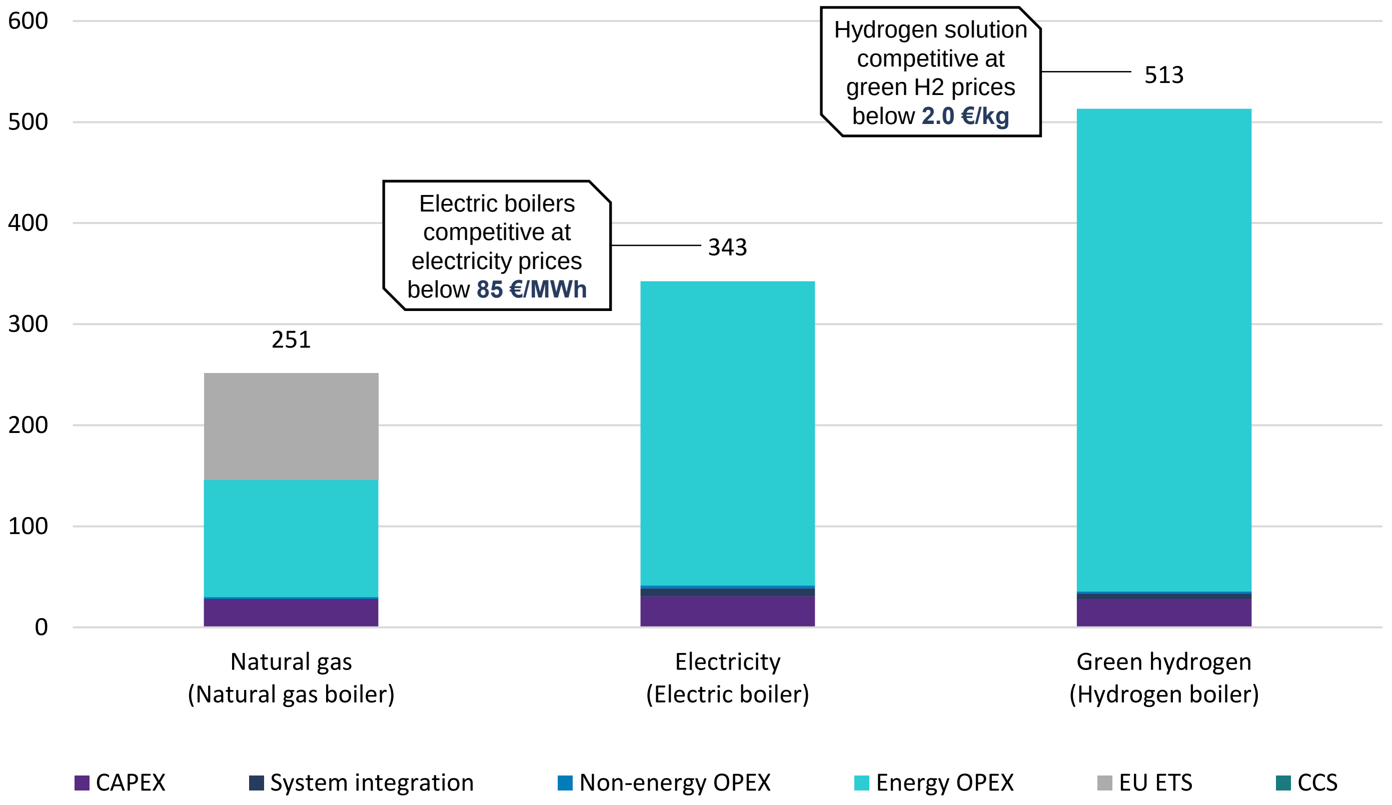


Key takeaways

Electric/hydrogen solutions

- **While the primary aluminium production process in the EU is already significantly electrified, some process steps in the upstream segment of the value chain – such as alumina refining – still run on fossil fuel but have electrification potential since they require lower temperatures**
- **While electric boilers are associated with comparable CAPEX to natural gas boilers, they are fully exposed to higher energy supply costs and electricity price volatility risks**
- **Green hydrogen could require lower prices to become economical, and direct electrification could be more suitable**

Energy production costs for 1 ton of post-digestion alumina (€/ton)

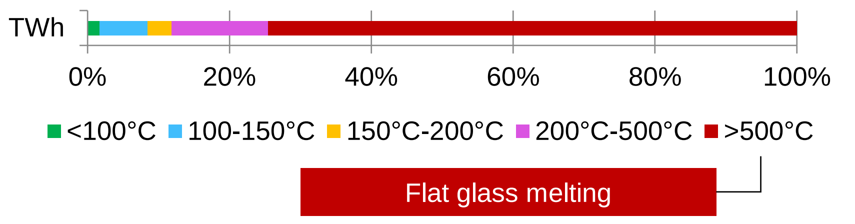


Source: Compass Lexecon analysis based on Germany's Federal Environment Agency's CO2-neutral process heat generation study (2023); Fraunhofer ISI's Direct electrification of industrial process heat study (2024); EC's 2040 Climate Target Impact Assessment (2024).
Note: In the economic assessment, no modernisation or re-investment costs are considered, and EU ETS costs represent the full EUA price with no free allocations. No CCS solution was considered as no pilot or demo project of carbon capture was identified.
Note: The EU-level energy consumption for non-ferrous metals is aggregated, while still noting that each metal is associated with different production processes and energy needs.

Case study 6: Flat glass melting – Economic potential for electrification

Electrification solutions are expected to face economic challenges in the medium-term, however low-carbon gas/electricity hybrid systems could serve as a temporary solution if cost parity is feasible

Non-metallic minerals – EU energy consumption per T°

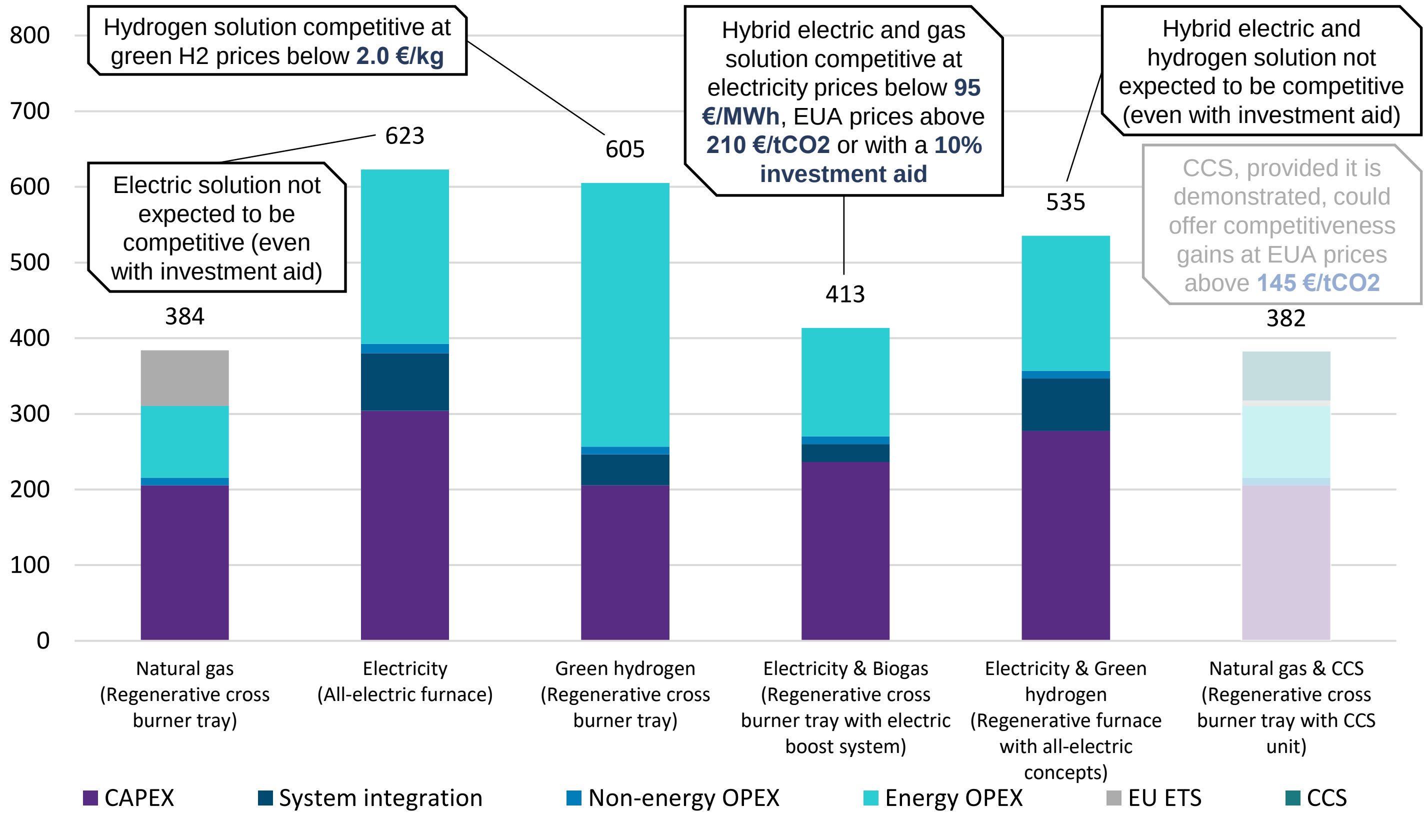


Key takeaways

Ⓒ Electric/hydrogen/hybrid solutions

- **The glass sector, and particularly the flat glass production process, is associated with very high temperatures and process heat requirements**
- **For flat glass, full-electric or green hydrogen-based systems are expected to still be associated with high CAPEX and/or high energy OPEX costs in the medium-term**
- **Hybrid partially-electrified systems that also rely on low-carbon natural gas could be interesting from a CAPEX and OPEX perspective in the long-term – especially considering that electric boost systems are already commonly used in the sector**

Energy production costs for 1 ton of post-melting flat glass (€/ton)

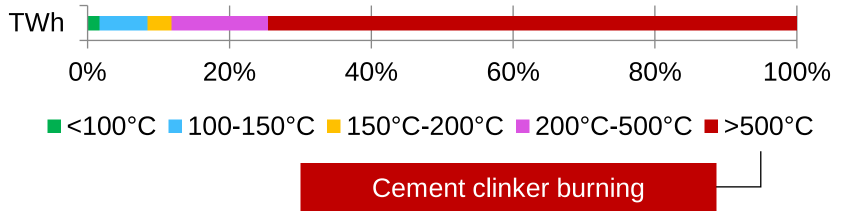


Source: Compass Lexecon analysis based on Germany's Federal Environment Agency's CO2-neutral process heat generation study (2023); Fraunhofer ISI's Direct electrification of industrial process heat study (2024); EC's 2040 Climate Target Impact Assessment (2024).
Note: In the economic assessment, no modernisation or re-investment costs are considered, and EU ETS costs represent the full EUA price with no free allocations. The CCS solution considered is an amine-based process with transport and storage costs also integrated (based on Caudle et al.'s research paper on Integrating carbon capture and utilisation into the glass industry (2023) and the Danish Energy Agency's Techno-economic assessment of CCS technologies (2024)).

Case study 7: Cement clinker burning – Economic potential for electrification

While full electrification is expected to be very challenging, hybrid bio-based solutions could offer some benefits in the long-term, but most emissions arise from the process itself, and CCS could be best suited

Non-metallic minerals – EU energy consumption per T°

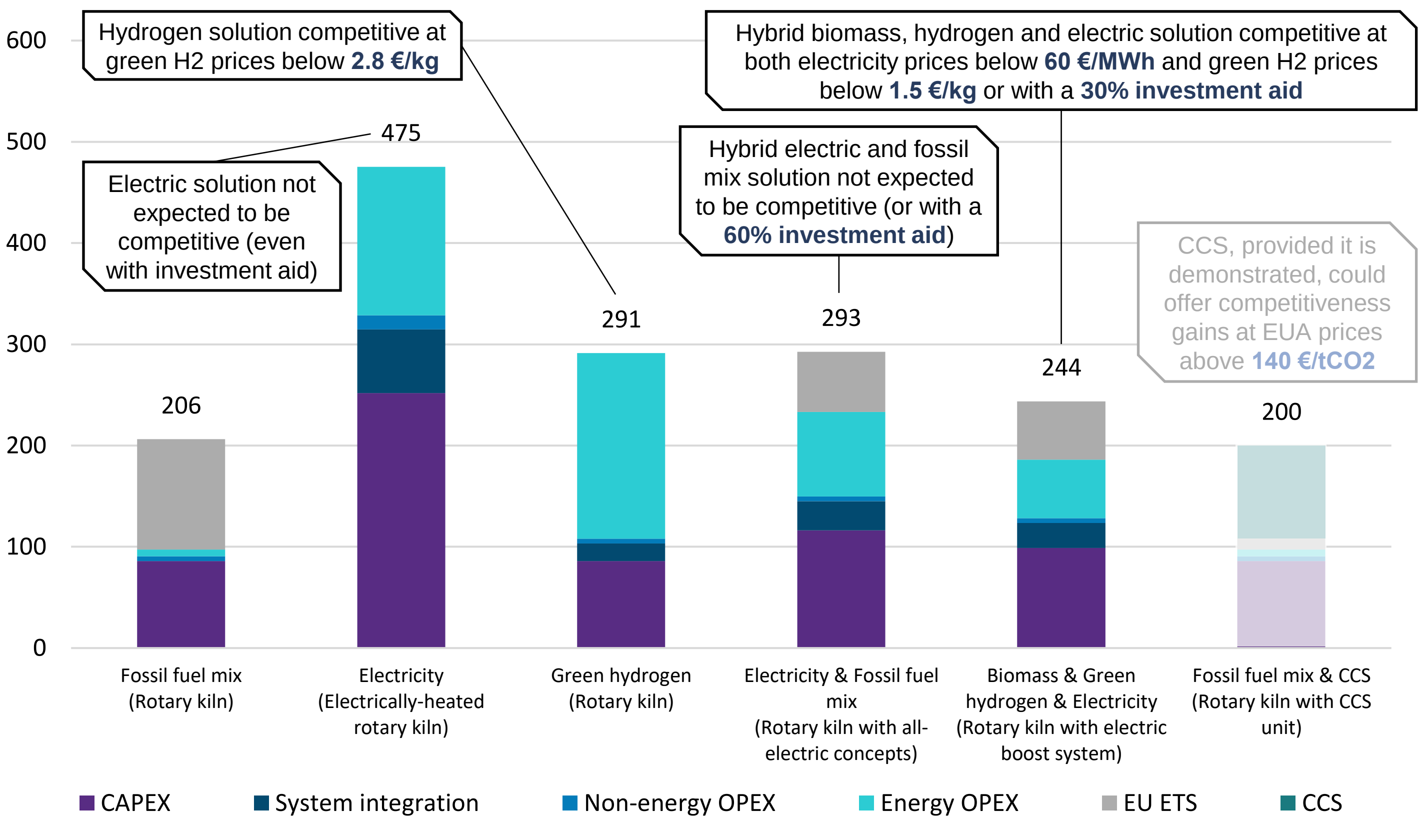


Key takeaways

Electric/hydrogen/hybrid solutions

- **The cement sector presents unique challenges due to its high temperature processes as well as its high emissions from both energy use and the reaction in clinker production**
- **For cement clinker, full-electric or green hydrogen-based systems are expected to still be associated with high CAPEX and/or high energy OPEX costs in the medium-term**
- **While partial electrification more than halves emissions, hybrid electric systems are expected to not have a strong business case in the medium term, with lower-cost biomass-based systems potentially having a role to play**
- **CCS could play a key role if electric and hydrogen-based solutions still face cost and scalability issues**

Energy production costs for 1 ton of cement clinker post-burning (€/ton)



Source: Compass Lexecon analysis based on Germany's Federal Environment Agency's CO2-neutral process heat generation study (2023); Fraunhofer ISI's Direct electrification of industrial process heat study (2024); EC's 2040 Climate Target Impact Assessment (2024).
Note: In the economic assessment, no modernisation or re-investment costs are considered, EU ETS costs represent the full EUA price with no free allocations, and the generation of electricity from the CHP plant is accounted for as energy OPEX reductions. The CCS solution considered is an amine-based process with transport and storage costs also integrated (based on the Danish Energy Agency's Techno-economic assessment of CCS technologies (2024)).

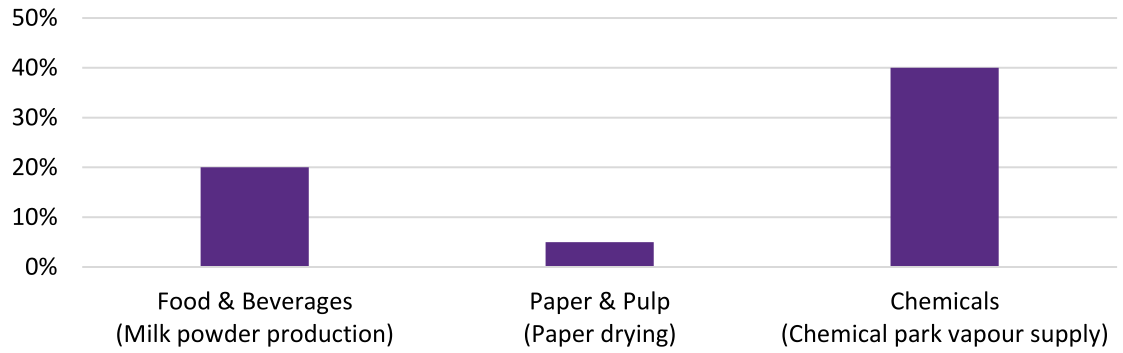
Focus: Heat pumps – Economic potential for electrification

While heat pumps could be cost competitive for sectors which use low temperature processes, CAPEX incentives may still be needed to incentivise technology adoption

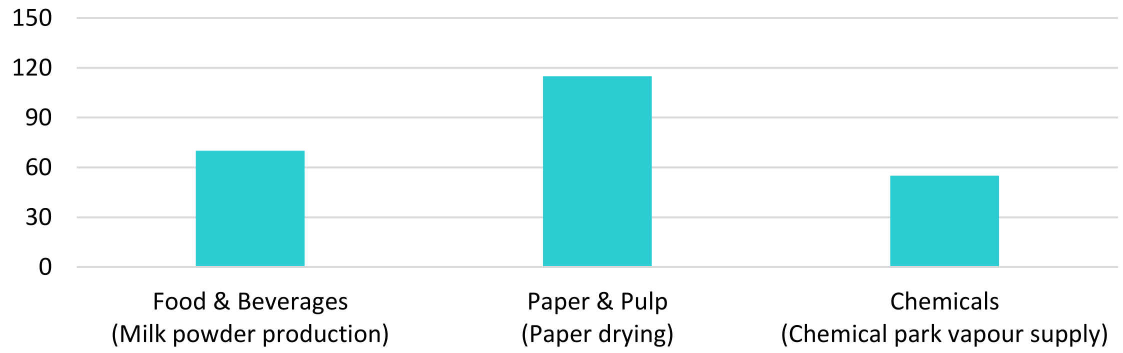
Heat pumps can limit the exposure to price volatility risks due to their high COPs, potentially allowing energy efficiency and energy OPEX reductions.

- Low-to-medium temperature industrial heat processes – such as in the food and beverages, the paper and pulp and the low-temperature chemicals sectors – could be electrified using heat pumps.
- While heat pumps are expected to offer advantages from an OPEX perspective, they are still associated with relatively high CAPEX compared to fossil-based technologies as well as other alternative low-carbon technologies such as electric boilers.
- Heat pumps can reach cost parity with incumbent technologies in all 3 sectors:
  - With a CAPEX reduction of between 5 and 40%;
  - With maximum input electricity prices between 60 and 110€/MWh.

Investment aid needed for heat pumps to achieve cost parity (CAPEX %)



Electricity price needed for heat pumps to achieve cost parity (€/MWh)



Source: Compass Lexecon analysis.
Note: The economic assessment assumes CAPEX for asset investments in 2025, with average prices over 2025-2045 of 120€/MWh for electricity, 40 €/MWh for natural gas, 165 €/MWh for green hydrogen and 150 €/tCO2e for EUAs.
Abbreviations: COP: Coefficient of Performance.

3. Barriers to industrial electrification

We analyse sector-specific barriers for the switch to electrification, building on insights from the economic assessment, expert inputs and literature

Economic cost assessment (Workstream 2)

Identification of costs (CAPEX/OPEX) for heat producing technologies

Assessment of costs for fuel switch on a subset of EU industry sub-sector applications (comparing CO2 intensive process and low-carbon process)

Expert interviews and stakeholder consultations (ERCST lead)

Conducting of interviews and stakeholder consultations to offer opportunities for stakeholders to share insights

Analysis of interview feedback and consultation responses regarding stakeholder’s insights on challenges related to electrification

Sectoral decarbonisation roadmaps (see Appendix)

Review of publicly available sectoral decarbonisation roadmaps of manufacturing industries (food and beverages, aluminium, cement, etc.)

Analysis of barriers to industrial electrification

Development of a framework for the analysis of sector-specific barriers building on expert inputs and public sources:

1. **Identification of key categories of barriers:** economic, technological, infrastructure, regulatory, supply chain and structural
2. **Examples of barriers** per category and industrial sector
3. **Analysis of the degree of intensity** of the key categories of barriers by sector (high or low barriers)

Source: Compass Lexecon analysis.

Industrial technology switches are subject to a range of barriers that can be grouped in six categories

1. Economic barriers	CAPEX	Economic viability of alternative technologies is challenged by high CAPEX due to necessary up-front investments and retrofitting efforts needed.
	OPEX	Economic viability of alternative technologies is challenged by high OPEX due to higher energy supply costs, sourcing difficulties and operational challenges as well as high exposure to energy market risks and price volatility, and possibly lower energy efficiency.
	Investment cycle	Risk of fossil-based technology lock-in and of stranded assets as investments are postponed given the lacking technological readiness of alternative technologies, the long investment cycles and the associated business risks of prolonged periods of stopped production.
2. Technological barriers	Technological properties	Required process parameters (temperature levels, pressure levels, energy density, uniform heat distribution, production volumes) are not fully met by alternative technologies. Feedstock incompatibility due to logistical and technical challenges could be an issue as well.
3. Infrastructure barriers	Network infrastructure	Connection delays, lack of available network capacities and lack of coordination between electrification and network development hamper the switch to electrification due to long lead times, risks surrounding stable and reliable supply and congestion risks.
4. Regulatory barriers	Regulatory framework	Inadequate regulatory frameworks, lack of adequate support frameworks and the imposition of stringent regulatory and environmental standards and requirements, among other factors, pose challenges in adopting low-carbon technologies due to a lack of incentives.
	Regulatory stability	Uncertainty about the development of political and regulatory direction as well as stringency, in particular related to fossil fuels and carbon pricing, hamper the switch to electrification.
5. Supply chain barriers	Labour force	Installation, monitoring and maintenance of alternative technologies may be challenged by shortage / unavailability of skilled labour.
	Input supply	Uncertainty about sufficient and reliable inputs supply after technology switch, in particular security of supply of electricity and availability of hydrogen, hamper the switch to electrification.
6. Structural barriers	Company size	In particular for SMEs, lack of access to required information and lack of skilled workforce as well as lack of access to financing are challenging.
	Company location	In particular for companies / plants in rural areas, challenges to meet infrastructure needs required for the technology switch are important.

Source: Compass Lexecon analysis.
Note: The list of barriers is not exhaustive.

Both the stakeholders’ consultation and our review of sectoral decarbonisation roadmaps allows to pinpoint key barriers in each category (1/2)

Category	Sub-category	**Key barriers** *(examples)*
Economic	CAPEX	➢ *High up-front investment costs* ➢ *High retrofitting and infrastructure costs*
	OPEX	➢ *High electricity-to-gas price ratio* ➢ *High green hydrogen costs* ➢ *High electricity price volatility* ➢ *Increase in raw material supply costs due to low-carbon origins*
	Investment cycle	➢ *Prolonged periods of production halt* ➢ *Long investment cycles and risk of stranded assets* ➢ *Risk of carbon intensive process lock-in due to lack of mature cost-efficient decarbonisation technologies*
Technological	Technological properties	➢ *High temperature and pressure process requirements* ➢ *High production volume and energy requirements* ➢ *Lack of availability of mature electrification solutions (low TRL)* ➢ *Logistical challenges in raw material and energy supply*
Infrastructure	Network infrastructure	➢ *Lack of coordination between electrification and network development plans* ➢ *Insufficient electricity grid capacity* ➢ *Electricity grid connection delays due to long permitting processes and large connection queues* ➢ *Congestion issues and localised constraints* ➢ *Lack of availability and/or proximity of connection points* ➢ *Limited interconnection capacity* ➢ *Lack of readiness of hydrogen network infrastructure and sufficient capacity*

Source: Compass Lexecon analysis based on sectoral decarbonisation roadmaps; inputs from industry representatives during the consultation process of the project; literature review.
Note: The list of barriers is not exhaustive.
Note: A qualitative and more detailed assessment of the different barriers per industrial sector as well as stakeholder responses can be found in the Appendix.
Note: Infrastructure barriers can vary greatly between different areas and regions

Both the stakeholders' consultation and our review of sectoral decarbonisation roadmaps allows to pinpoint key barriers in each category (2/2)

Category	Sub-category	**Key barriers** *(examples)*
Regulatory	Regulatory framework	➢ *Stringent product quality and compliance standards* ➢ *Stringent climate and environmental regulations and emission standards* ➢ *Lack of adequate support framework, including dedicated CAPEX funding support* ➢ *Lack of a realistic anti-carbon leakage and post-2030 EU ETS framework* ➢ *Lack of adequate permitting processes as well as integration provisions*
	Regulatory stability	➢ *Uncertainty regarding the evolutions of environmental standards and compliance requirements* ➢ *Uncertainty on the status of biogas, biomass and/or renewable waste as "renewable"* ➢ *Uncertainty regarding EU ETS evolutions*
Supply chain	Labour force	➢ *General shortage of skilled labour*
	Input supply	➢ *Electricity security of supply risks* ➢ *Lack of available and affordable renewable electricity* ➢ *Lack of available and affordable green hydrogen* ➢ *Lack of available and suitable low-carbon inputs*
Structural	Company size	➢ *Large size as potential issue due to higher energy requirements* ➢ *Small size as potential issue due to risk of limited adaptability (access to information, limited portfolio / skills)*
	Company location	➢ *Risk of long distance from available (low-carbon) energy infrastructure* ➢ *Lack of available suitable low-carbon inputs* ➢ *Risk of higher input and energy prices*

Source: Compass Lexecon analysis based on sectoral decarbonisation roadmaps; inputs from industry representatives during the consultation process of the project; literature review.
Note: The list of barriers is not exhaustive.
Note: A qualitative and more detailed assessment of the different barriers per industrial sector as well as stakeholder responses can be found in the Appendix.

The outcome of the stakeholder consultation process highlights that industries facing high economic barriers are also associated with important non-economic challenges

- Our assessment of the different barriers to the adoption of electrification technologies in industrial applications is based on the economic assessment, inputs from industrial representatives and experts through interviews and consultations as well as public sources, including sectoral decarbonisation roadmaps.

Industrial sector ▶ Barriers ▼		Food & Beverages	Paper & Pulp	Chemicals (Low °T)	Chemicals (High °T)	Iron & Steel	Aluminium	Glass	Cement
Economic	CAPEX								
	OPEX								
	Investment cycle								
Technological	Technological properties								
Infrastructure	Network infrastructure								
Regulatory	Regulatory framework								
	Regulatory stability								
Supply chain	Labour force								
	Input supply								
Structural	Company size								
	Company location								

Low barrier — High barrier

Source: Compass Lexecon analysis based on sectoral decarbonisation roadmaps; inputs from industry representatives during the consultation process of the project; literature review.
Note: A qualitative and more detailed assessment of the different barriers per industrial sector as well as stakeholder responses can be found in the Appendix.

4. Potential measures to support the decarbonisation of industrial processes

Potential measures for successful electrification can be grouped into complementary categories, of which securing abundant competitive low-carbon energy supply is central

- Based on the stakeholder consultations as well as our analysis of available public sources, potential measures to promote and incentivise industrial electrification can be grouped into four complementary categories.
- Note that stakeholders have suggested during the consultation process that due to limited amounts of EU funding / State Aid, relying on trade policy could be needed. However, this is not in the scope of the analysis in this report.

Focus of the analysis

Principle	**Lifting Non-economic Barriers**	**Securing Abundant Competitive Low-carbon Energy**	**Providing Cost-effective Investment and Operating Aid**	**Using sectoral trade policy**
Potential measures	▪ **Infrastructure**: EU coordination, accelerating permitting, anticipatory investments, grid enhancing technologies, flexible connections and digitalisation ▪ **Technological**: EU coordination, funding research, clean technology investment focus ▪ **Regulatory**: stable EU ETS and CBAM rules, aligning standards with low-carbon processes, avoid over-complexity ▪ **Supply chain**: applying circular economy principles, training and attracting skilled talent ▪ **Structural**: centralised information sharing, access to financing for SMEs	▪ **Delivering abundant and competitive low-carbon energy supply**: boost low-carbon energy production, accelerate grid infrastructure development, accelerate flexibility development ▪ **De-risking low-carbon electricity supply for large energy users**: boost development of power purchase agreements, boost long-term contracts and forward hedging, support industrial renewable electricity self-consumption ▪ **Aligning energy taxation on climate goals**: revise tax levels on gas, electricity and other energy carriers' usage in industrial processes	▪ **Optimising the use of EU funds and State Aid using principles from carbon leakage mitigation framework**: provide both operating and investment aid for most trade- and GHG-intensive industries when relevant, or only investment aid when relevant ▪ **Optimising the use of EU funds and State Aid by accounting for international competitiveness**: include international competitiveness of energy costs in business-as-usual scenario definition to address energy costs gap	▪ **Sectoral border taxes:** review EU trade policy overall to shield most at-risk industries at least during the transition phase

Source: Compass Lexecon analysis based on inputs from stakeholders during the consultation process of the project; literature review.
Abbreviations: CBAM: Carbon Border Adjustment Mechanism.

4.1 Potential measures to lift non-economic barriers

The availability of the power infrastructure is a key barrier, potential measures to lift it include permitting, standardisation, coordination and anticipatory investments

- Accelerating the required investments to adapt and connect new end-uses to the power grid can rely on a range of measures such as speeding up permitting, increase EU coordination, incentivising anticipatory investments and securing the power grid supply chain. In addition, the implementation of smart meters with advanced functionality to provide real-time price signals is key for the scale up of Demand-Side Response.
- Note that we have not reviewed potential measures exhaustively.

Infrastructure barriers	
Connection delays and lack of available network capacities	
Potential mitigation	**Addressed EU level**
Development and modernisation of the transport infrastructure through the implementation of digital tools and grid enhancing technologies (smart grid deployment)	EU grid action plan
Simplify and speed up **permitting** (additional human resources, digitalisation)	EU grid action plan, Technical Support Instrument Regulation
Simplify and accelerate the development of cross-border **interconnections** infrastructure within the EU and identify priority corridors	Revised Trans-European Networks for Energy Regulation, Project of Common Interest program, Project of Mutual Interest program
Promote the **standardisation and interoperability** of technologies to ensure the integration of demand-side response (DSR)[1] solutions into the grid	European Union Agency for the cooperation of Energy Regulators (ACER) report on Demand response[2]
Make use of the "overriding public interest principle" to increase the pace of the deployment of grid investments	RED III, EU Grid action plan, European Union Agency for the cooperation of Energy Regulators (ACER) report on Demand response[2]
Make use of **anticipatory investment** and promote holistic system **coordination** between demand for electricity and **grid planning**	EU grid action plan, Revision of Electricity Market Design
Develop European manufacturing capacity for critical grid infrastructure components (transformers, cables, switchgear, etc.).	EU grid action plan

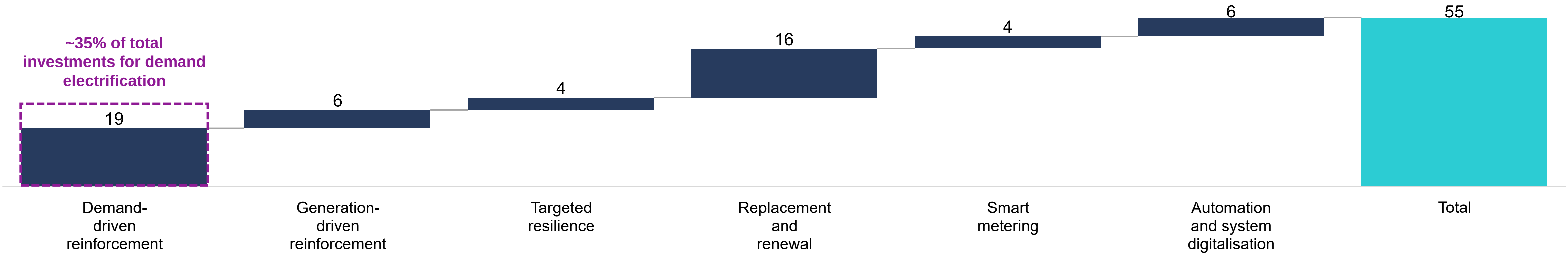
Source: Compass Lexecon analysis.
Note: (1) DSR is the measure of adjusting or reducing electricity usage by consumers during peak demand times or in response to supply constraints. (2) The report mentioned here is ACER's 2023 Market Monitoring Report on Demand response and other distributed energy resources.

Electricity grid expansion is critical, with large investments planned to integrate renewables and the electrification of end-uses

Investments in electricity grids are needed to guarantee a secure, reliable and decarbonised energy system. Anticipatory investments and flexible connection agreements have the potential to ease connection delays.

- Substantial increase in grid investments are needed to integrate distributed renewable energy sources and electrify final consumption in the industrial, building and transport sectors. A recent study published by Eurelectric estimates that the total investment needs for grids in the EU between 2025 and 2050 could be at minimum 55 bn€ per year, mainly for grid reinforcements and replacements.
- Perceived grid-related barriers for industrial development (e.g., curtailments, connection delays, hosting capacity) are time- and geography-related and can be overcome with adequate investments. Notably, anticipatory investments have been identified as a regulatory tool to accelerate needed connections, by proactively expanding grid capacity assuming – with sufficient level of certainty – that new generation and demand (e.g., industrial hubs) will materialise.
- In the short-term, flexible connection agreements are seen as a potential tool to ease connection delays and network investment costs, as mentioned in Directive (EU) 2024/1711.
- Finally, the electrification of end-uses allows to spread the investment costs over a larger electricity consumption, limiting the rise of individual consumers' grid fees.

Annual average grid investments – EU-27 countries and Norway, 2025-2050 (bn€ nominal)[1]



Source: Compass Lexecon analysis based on Directive (EU) 2019/944; Eurelectric's Grids for Speed report (2024); EC's Joint Research Centre (JRC)'s 2023 Status Report on Smart Grids in the European Union; ACER's 2023 Market Monitoring Report on Energy Retail and Consumer Protection; ENTSO-E's Legislative Proposal for a Regulation to Improve the Union's Electricity Market Design (2023).
Note: (1) Investments in nominal terms are derived using a standard PPI at country level, based on Eurelectric's Grids for Speed report (2024), and as of end 2022, based on EC's Joint Research Centre (JRC)'s 2023 Status Report on Smart Grids in the European Union.

Technological and regulatory barriers are perceived as additional risks and can be addressed through a variety of potential measures

- Some manufacturing processes still lack adequate or mature decarbonisation options, which can be addressed by securing fundamental research funding, knowledge sharing and coordination at EU level and accelerating approvals and permitting for new clean technologies.
- Uncertainties associated with climate regulations and incompatibility between low-carbon production processes and some safety standards would be improved by avoiding over-complexity, align standards with new technologies, and providing long-term stability of the climate policy framework.
- Note that we have not reviewed potential measures exhaustively.

Technological barriers		Regulatory barriers	
Required process parameters (temperature level, pressure, energy density, uniform heat distribution) not fully met by alternatives or feedstock incompatibility		Inadequate regulatory frameworks and regulatory requirements for new technologies, as well as uncertainty about the development of political and regulatory direction, including stringency, in particular related to fossil fuels and carbon pricing	
Potential mitigation	**Addressed on the EU level by**	**Potential mitigation**	**Addressed on the EU level by**
Secure **fundings for fundamental research** and technological development	Horizon Europe, European Institute of Innovation and Technology	**Avoid over-complexity** in the definition, implementation and monitoring of new low-carbon energy carriers required to decarbonise heavy emitting processes	Cited in Draghi's Report[1] (but not officially addressed at EU level)
Incentivise **collaboration and coordination** between Member States	European Research Area Net (ERA-NET)	**Align standards and safety regulations** with innovative low-carbon technologies' capabilities on a sector specific basis	—
Focusing **investment on clean-technology sectors** where the EU has a competitive advantage	Cited in Draghi's Report[1] (but not officially addressed at EU level)	Provide **long-term predictability on regulatory framework** on a sector specific basis, e.g**. clear decarbonisation goals**	—
Simplified and shorter permitting processes to support the deployment of net-zero technologies	Net-Zero Industry Act RED III	Ensure that every industry has its **dedicated industrial plan**	The Green Deal Industrial Plan
		Establish **green quota procurements** for low-carbon EU products	—

Source: Compass Lexecon analysis.
Note: (1) The report mentioned here is Mario Draghi's 2024 report on The future of European competitiveness.

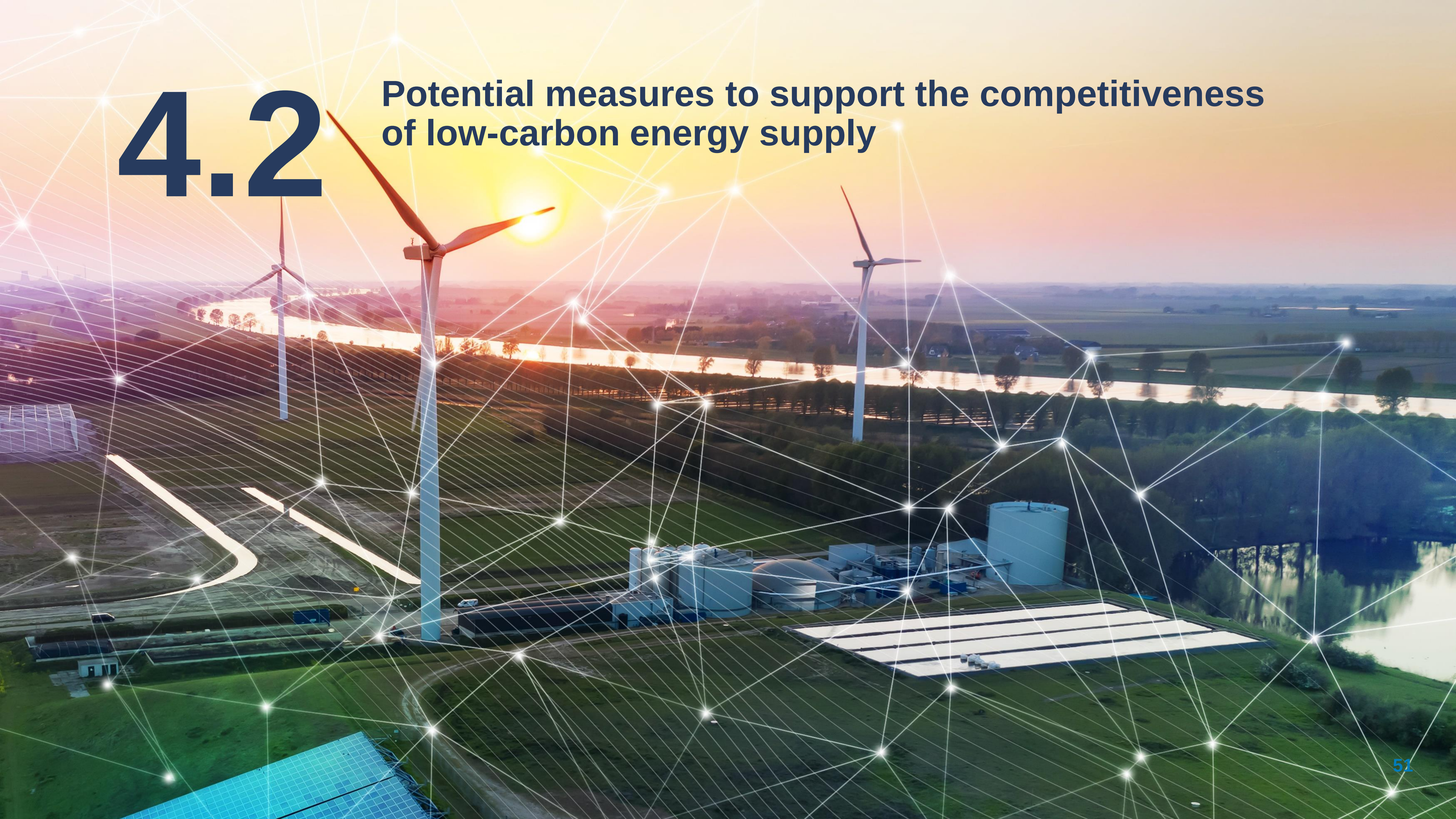
Risks of low-carbon production supply chain disruptions and structural limitations such as companies' sizes or access to financing can be improved with EU coordination

- Securing the supply chain of low-carbon products manufacturing can, for example, rely on domestic mining, securing critical materials and developing the circular economy, as well as with dedicated training and talent attraction programs.
- Structural limitations in some sector can be overcome for example using EU coordination, improving access to information (on technologies, costs estimates and business models) and streamlining access to financing for smaller companies .
- Note that we have not reviewed potential measures exhaustively.

Supply chain barriers		Structural barriers	
Issues that disrupt the implementation, maintenance, and flow of resources necessary for a supply chain to function effectively such as shortage of skilled labour or energy security of supply risks		Additional system-wide or sector specific issues hindering the process of decarbonisation of industrial sectors such as companies' sizes or location or access to funding	
Potential mitigation	**Addressed EU level**	**Potential mitigation**	**Addressed EU level**
Developing **domestic extraction** capacities of targeted raw materials within the EU	Critical raw material act	Ensure that actors of all sizes are aware of and have **access to key information** to support their decarbonisation initiatives	EU project development assistance
Diversifying critical material import sources and be involved in implementing key infrastructure in collaboration with partner countries	Global Gateway program Critical raw material act	Realign a large share of EU ETS revenues and allocated subsidies for the decarbonisation of energy-intensive industries to **improve access to financing**	Cited in Draghi's Report[1] (but not officially addressed at EU level)
Strengthening of the EU **circular economy** environment and increasing the efficiency of recycling chains	EU Batteries Regulation Critical raw material act	**Streamline accessibility of financing solutions to SMEs**	—
Develop **targeted training** and specialised education program to increase the available skilled labour force	EU action plan on Labour and skills shortages		
Develop policies to **attract talents from outside** the EU and ease integration of foreign workers into the EU labour market	EU action plan on labour and skills shortages		
Ensure all companies operating in the EU assess **environmental and human right compliance** and are subject to similar norms	EU Corporate Sustainability Due Diligence Directive		

Source: Compass Lexecon analysis.
Note: (1) The report mentioned here is Mario Draghi's 2024 report on The future of European competitiveness.

4.2 Potential measures to support the competitiveness of low-carbon energy supply



Meeting EU Net-Zero targets while ensuring competitiveness of manufacturing industries requires to secure the availability of abundant, competitive low-carbon energy supply

- The cost-efficiency of subsidies is tied to the ability of the Union to deliver abundant, competitive low-carbon energy supply to all consumers, including manufacturing industries. Minimising the ‘decarbonisation costs gap’ could bring substantial benefits and relieve pressure on States’ budgets.
- Potential measures to deliver abundant and competitive low-carbon energy supply have been addressed in many reports in the past as well the EU Electricity Market Design Reform. We thus focus on innovative measures to reduce risks of low-carbon energy supply for industrials and energy taxation.

Focus of the section

	1 Delivering abundant and competitive low-carbon energy supply	2 Reducing risks of low-carbon electricity supply for large energy users	3 Aligning energy taxation on climate goals
EU framework	**EU Electricity Market Design Regulation, Renewable Energy Directive, Wind Action Plan, Grid Action Plan…**	**EU Electricity Market Design Regulation**	**EU Energy Taxation Directive**
Potential measures	▪ Boost **low-carbon energy production development** by lifting permitting and grid access issues ▪ Accelerate the development of **grid infrastructure and interconnections** through securing the supply chain, reforming incentive regulations of TSOs/DSOs and anticipatory investments ▪ Accelerate **flexibility development** on power grids through market design and investment frameworks	a) Boost **PPA development** through demand pooling, utility tokens, public guarantees, cumulation of CfDs and PPAs b) Boost **long-term contracts** and forward hedging through market design c) Allow industrials developing **flexible processes** to value their flexibility in power markets ▪ Facilitate the exchange of renewable electricity in the EU by establishing common guarantees of origin (GO) ▪ Support “on-site” or “off-site” industrial renewable electricity self-consumption through investment frameworks and CfDs	a) Revise **tax levels** on gas, electricity, biomass, and other energy carriers' usage in industrial processes
Limitations	▪ Cheapest energy source might still be more expensive than in other regions for structural and physical reasons	▪ Potential to allocate energy system costs between users differently but does not provide direct subsidy ▪ Subject to implementation of RED III and EMD provisions by MS	▪ Increases pressure on industrial costs for those remaining fossil-based

Source: Compass Lexecon analysis.
Abbreviations: TSO: Transmission System Operator; DSO: Distribution System Operator; PPA: Power Purchase Agreement; CfD: Contract-for-Difference, MS: Member States.

② Potential measures to reduce risks of low-carbon electricity supply for large energy users

2.a/b - A range of measures to de-risk electricity and low-carbon energy purchases for companies can be implemented with various degrees of political intervention in the market

Less complex intervention ⟷ **More complex intervention**

PPA intervention

Removing barriers to PPAs	State buyer	Public guarantees to SMEs	Centralisation of long-term contracts	State-run green power pool
Regulatory, policy, economic or other barriers limit the uptake of PPAs	As a large consumer, the State engages in PPAs to stimulate investment	Broadening the off-taker base by offering public guarantees when smaller parties engage in PPAs	A public agency acts as the sole central counterparty for PPAs and/or CfDs, overtaking this risk	A public agency runs a RES power pool, with standard PPA contracts to enable secondary trading

Forward market intervention

Easing of collateral regulations in forward markets	Expansion of volume and maturity of LTTRs	Voluntary mechanism to stimulate long term liquidity	Incentives for RES under support scheme to hedge
Collaterals accepted by CCPs should be accessible for the wider energy clearing industry	Introduction of 3-year tenor LTTR to match at least forward market product maturities	Selected entities must post minimum buy and sell orders with a maximum bid-ask spread, to boost liquidity	Adapting support linked to day-ahead prices to provide incentives to hedge in forward markets

Source: Compass Lexecon analysis.
Abbreviations: CCP: Central Counterparty; LTTR: Long-term transmission rights.

② Potential measures to reduce risks of low-carbon electricity supply for large energy users

2.a - Different mechanisms have already been implemented to facilitate and/or incentivise the development of PPAs

Purpose	De-risking mechanisms *(examples)*	Countries of application
Acceleration of adoption of PPAs and reduction of barriers for developers	Counterparty Risk Guarantee Fund for developers	Spain, France, Norway
	Obligation to source with green PPAs for large users	Spain
	Platform for bringing together supply and demand	Spain, Italy
Favouring cumulation of PPA and public support	Possibility to cumulate public support mechanisms (through tenders or green certificates) with a PPA	Netherlands, Germany, France, Belgium, United Kingdom, Denmark, Norway, Sweden, Finland, Poland
Design of support mechanisms	Support mechanisms with exposure to market price	Netherlands, Norway, Sweden
	Absence of volume limitations in public support	Spain, Italy, Finland
	Capped public support schemes (€/MWh)	Denmark
	Time-limited public support schemes (10-15 years)	Netherlands, Denmark, Norway, Sweden, Finland

Country Example (France)

In 2022, France announced a public guarantee fund for PPAs aimed at industrials starting in 2023, which supports onshore wind and solar PV projects and requires contracts with a 10-year minimum duration.

Country Example (Spain)

In 2022, the Spanish market operator OMIE announced the launch of 5–10-year PPA contracts for futures of baseload and solar profiles with underlying delivery in Spain.

Source: Compass Lexecon analysis based on E-Cube's Analysis of the dynamics and public support mechanisms for renewable energies favourable to PPAs in Europe (2022).
Note: The list of de-risking mechanisms as well as the list of countries of application are not exhaustive.

② Potential measures to reduce risks of low-carbon electricity supply for large energy users

2.a Case study – Spain has the largest and most dynamic renewable PPA market in Europe, in part due to public guarantees which have helped develop PPAs for large electricity consumers

Spain has the largest PPA contracted capacity in Europe, with a 23% share of the total European renewable PPA market.

Spain's public guarantee scheme has contributed to making its PPA market the most dynamic in Europe.

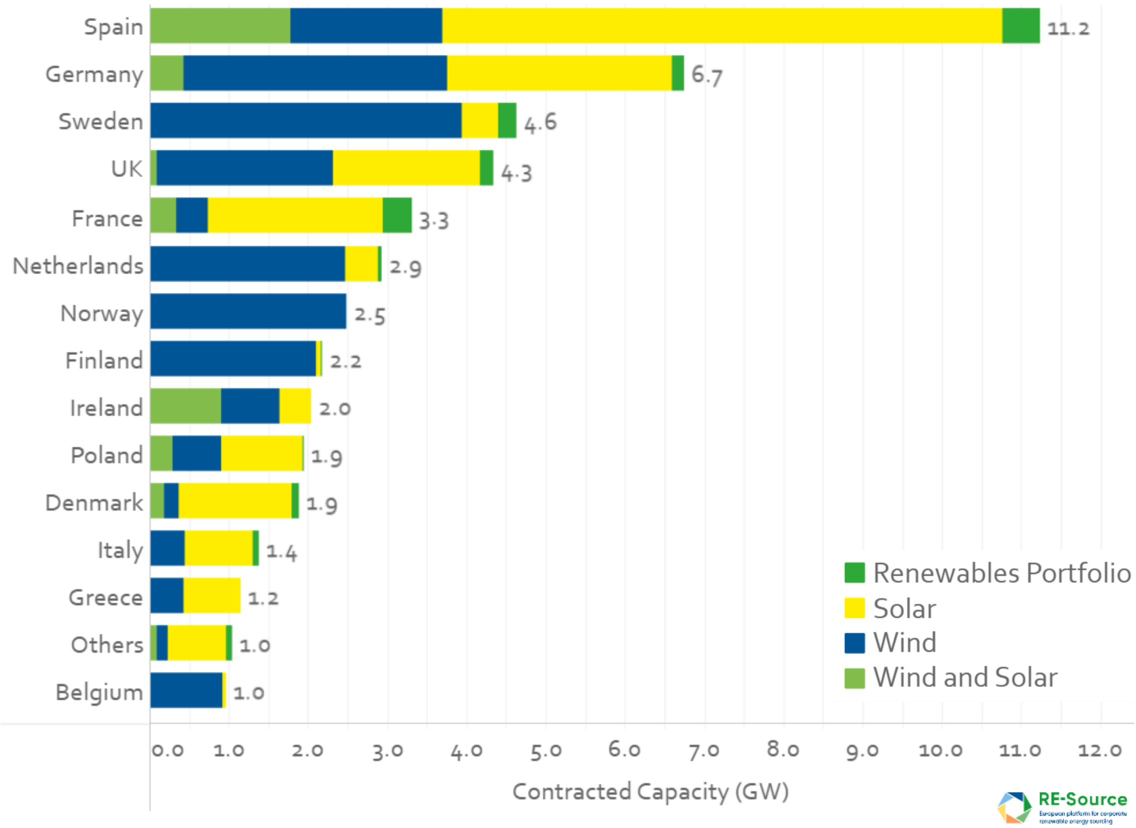
PPA sourcing obligations for large users

- The Royal Decree 1106/2020 requires large electro-intensive users with a consumption of more than 1 GWh to source at least 10% of their power consumption with a PPA contract of a minimum duration of 5 years.
- Electro-intensive users are required to show their coverage 1 year after the entry to force of the Decree, or when they acquire the status of large electro-intensive user.

PPA sourcing obligations for large users

- Royal Decree 1106/2020 also introduced a Reserve Fund to Guarantee Large Electricity Consumers (FERGEI) to encourage PPAs.
- This fund offers guarantees for generators with PPAs for large electro-intensive users, and insurance/bank guarantees in the event that an off-taker cannot meet its obligations (due to insolvency/non-payment, for example). It covers PPAs with a duration between 5 years and 20 years.

European renewable PPA contracted capacity by country – 2024 (GW)



Source: Compass Lexecon analysis based on Spain's Royal Decree 1106/2020; 2024 data from the European platform for corporate renewable energy sourcing.
Note: Country-level contracted PPA capacity data is as of end of November 2024 and the figure shows countries with a PPA capacity of at least 1 GW.

② Potential measures to reduce risks of low-carbon electricity supply for large energy users

2.a Case study – The centralisation of long-term contracts through the central counterparty model supports PPAs by transferring counterparty risk away from market participants and to the State

The issue:

- The relatively long maturity of PPA contracts implies that each party must be resilient over the long run to reassure the other party to engage in such arrangements.
- Risks for buyers when entering into a long-term renewable PPA are a barrier compared to traditional electricity contracts: legal, credit, volume risks, etc.

The state central counterparty mechanism:

- A State entity could become a central PPA counterparty, which could be taking on the counterparty risk of both parties – if one bankrupts, the State remains in charge of honouring the contract.

Advantages:

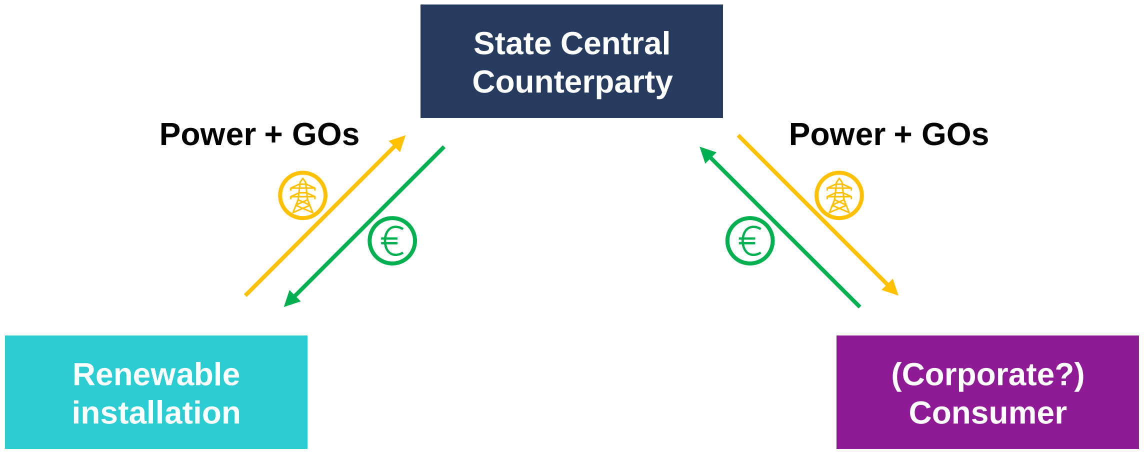
- Less risk for contracting parties, particularly for long PPA maturity – this can help PPAs develop.
- Centralised counterparties can help standardise contracts, as the basis for secondary trading.

Drawbacks:

- Risk is borne by consumers through the State entity.
- Capability, information and expertise required for the central counterparty.

PPA Central Counterparty model — Illustrative

A State central counterparty to intake counterparty risk in long- term PPA contracts



Source: Compass Lexecon analysis.

② Potential measures to reduce risks of low-carbon electricity supply for large energy users

2.c Case study – Industries that can provide flexibility to power grids should be incentivised to do so to create value for both the power system and the industrials

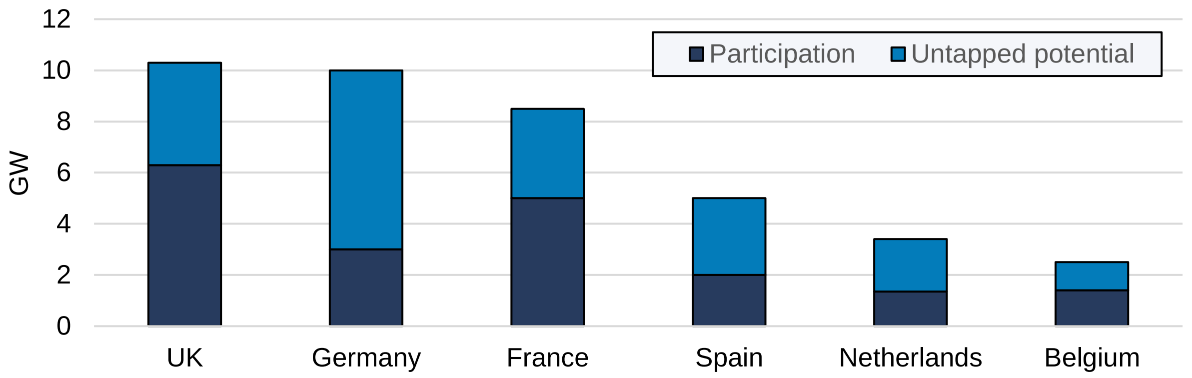
There is an important potential for additional industrial flexibility in Europe.

- Demand side flexibility enables to bring some necessary flexibility in the power system with lower need for generation or storage.
- There is an important potential for industrial flexibility estimated to 100GW in 2019, that is projected to grow to 160GW by 2030.

Industrial flexibility can help achieve decarbonisation objectives if suitable policies are backing its development.

- Some policies can facilitate the development of industrial flexibility:
  - Addressing barriers to the effective market participation of flexible resources (Restrictive or deterrent rules).
  - Ensure that the market design adequately reflects the full value of this flexibility for the power system.
  - If necessary, create a specific de-risking contractual and regulatory framework (Such as interruptibility schemes or capacity/flexibility markets).
- Appropriate policies and investment framework should incentivise the participation of least-cost and most flexible processes.
- On an industry-specific basis, there is a need to conduct additional pilot projects that demonstrate the flexibility of existing processes, in order to better understand their technical constraints.(1)

Participation and potential of industrial demand response (GW, 2020)



Suitable markets and remuneration for industrial demand response

Market	Remuneration
Day-ahead market	Energy cost savings by optimising plant operation hours to avoid high price periods, thereby reducing load cost
Capacity market	Payments for participating in energy markets, particularly during periods of grid stress (periods with risk for security of supply)
Ancillary services	Reducing load within a short response time to help balancing consumption and production in near real-time
Interruptibility scheme	Specific schemes for large industrials to be remunerated to curtail load when called, usually in rare occasion (c. 5 to 25 times a year)

Source: CL analysis based on Tennet, Strategy&: Unlocking industrial demand side response (2023)
Note: All € figures are expressed in real 2023 unless otherwise stated.
Note: (1) As an example, the dependencies between industrial processes can result in high levels of constraints.

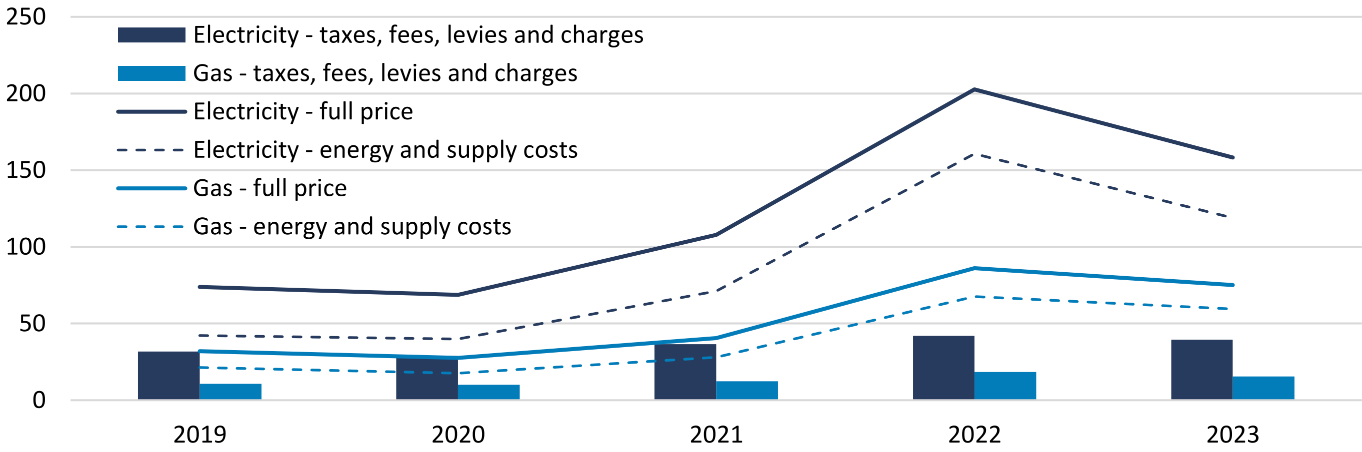
3 Snapshot on the current state-of-play of energy taxation

3.a. Reforming energy taxation in the EU is an important leeway as it currently favours gas over electricity in most Member States

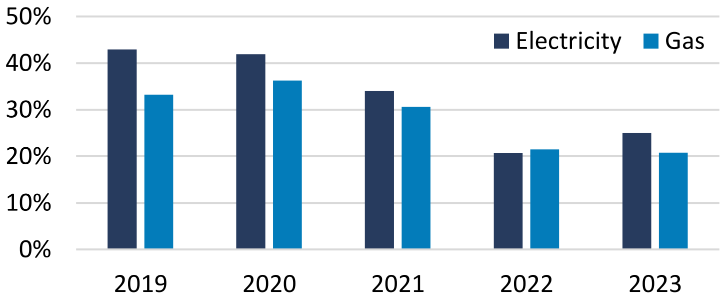
Current taxation policy across EU Member States favours the use of natural gas over electricity.

- Despite the EU's Energy Taxation Directive setting **comparable minimum taxation rates** for businesses at 0.54 €/MWh (0.15 €/GJ) for natural gas and 0.5 €/MWh for electricity, the actual **taxation rate for electricity has been higher than that for natural gas** – except during the energy crisis.
- On average over the last 5 years, taxes have been around 40% of energy supply costs for electricity and 35% for natural gas. The electricity-to-price ratio has been around 2.5 – including taxes and discounting the unintended effects of the energy crisis.
- However, around **two-third of electricity tax revenues have been used to subsidise renewable energy** and support infrastructure development, which partially mitigates the disincentive effect of taxation.
- A key limitation of rebalancing gas and electricity taxes would be to further threaten the competitiveness of industries remaining fossil-based.

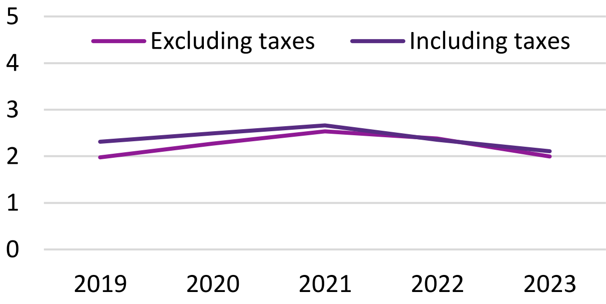
Average electricity and natural gas prices for industrials – EU-27, 2019-2023 (€/MWh)



Share of energy prices attributable to taxes



Electricity-to-Gas price ratio



Source: Compass Lexecon analysis based on Eurostat data; EC's Energy Taxation Directive (2003/96/EC).
Note: In Eurostat, gas price components are considered for the average band of all non-household consumers and electricity price components are considered for the band IG designating non-household consumers with a consumption of 150,000 MWh or over.

4.3 Potential mechanisms to address the industrial decarbonisation cost gap

An expanded framework to fund timely decarbonisation in industry could combine economic principles underpinning EU funds, State Aid and the carbon leakage framework

- A policy toolbox is available at EU-level to bridge the decarbonisation cost gaps in sectors that face the most challenge to decarbonise. It can combine principles from both the carbon leakage risk mitigation policies, the State Aid mechanisms and the EU funds.
- The carbon leakage mitigation framework was presented in Slide 31; thus, we focus in this section on State Aid and EU Funds' principles and limitations.

Focus of the section

	1 Carbon leakage mitigation	2 State Aid for environmental protection	3 EU Funds
Key relevant principles	▪ Eligibility / necessity depends on GHG / energy intensity ▪ Eligibility / **necessity depends on trade intensity** (exposure to international competition)	▪ **Competitive** bidding ensures proportionality of the aid ▪ Covers both **investment aid and operating aid** ▪ Can be built on **contracts-for-difference**	▪ **Competitive** bidding ensures proportionality of the aid ▪ Covers both **investment aid and operating aid** ▪ **EU-level aid** allows coordination across Member States ▪ Based on **best-in-class projects** across Member States
Potential measures	▪ Implement aid based on trade intensity, price differential with international competitors and GHG intensity criteria	▪ Use the **CEEAG framework to support industrial decarbonisation** to bridge the competitiveness **funding gap** ▪ **Expand the use of CfDs and CCfDs** to support the decarbonisation of industrial sites	▪ Supporting **industrial competitiveness and economic growth** in the EU through an "Electrification and Decarbonisation Bank" (one stop shop)
Limitations	▪ Does not address energy cost competitiveness or investment cost competitiveness between technologies or compared to international competitors	▪ Based on national initiatives with various capabilities across Member States, and availability of funding might not be commensurate to pan-European needs	▪ Availability of funding might not be commensurate to pan-European needs

Source: Compass Lexecon analysis.
Abbreviations: CCfD: Carbon Contract-for-Difference.

② State Aid for environmental protection

The State Aid Guidelines for environmental protection highlight possibilities for Member States to implement investment and operating aid for industrial decarbonisation

The Guidelines on State aid for climate, environmental protection and energy (CEEAG, 2022) provide the framework for State Aid to decarbonise manufacturing industries

- Economic principle is based on the decarbonisation costs ('funding') gap between business-as-usual processes and low-carbon processes.
- Thus, incentives may be granted, in the form of CAPEX and OPEX subsidies.
- For both CAPEX aid, a key issue is the calculation methodology, and notably the reference case adopted.
- For CAPEX and OPEX aid, a key issue is the calculation methodology and the reference case as well as the duration of the incentives.
- Finally, the State Aid framework allows "Operating aid" in limited cases and just for renewables support funding levies.

Overview of the CEEAG's principles

	Climate, Energy and Environmental Aid Guidelines (CEEAG)
General principles	*Possibility to grant aid for GHG emission reduction initiatives including industrial decarbonisation*
Investment and Operating Aid	▪ Granting of Aid is based on '**funding gap**', i.e., difference between cashflows of low-carbon investment and business-as-usual alternative ▪ Granting of Aid through competitive bidding is preferred ▪ Market-wide approach is preferred unless risk of significant deviation between the bid levels that different categories of beneficiaries are expected to offer ▪ Aid intensity shall not exceed 40% of the eligible costs unless the aid is granted by competitive bidding (up to 100% of eligible costs)
Operating Aid	▪ Only allows reductions in certain electricity levies (RES-E support charges) for industries that have been identified as being electro-intensive and at the same time open to international trade

In addition, the General Block Exemption Regulation (GBER) updated with Regulation 2023/1315, Article 36, allows State aid without notification to the European Commission up to 30 M€ per undertaking per project for investments.

Source: Compass Lexecon analysis based on EC's Guidelines on State aid for climate, environmental protection and energy 2022; Regulation (EU) 2023/1315.
Abbreviations: RES-E: Renewable Energy Sources-Based Electricity.

② State Aid for environmental protection

Member States have started using the CEEAG framework to support industrial decarbonisation…

Member States have started using the CEEAG State Aid framework to cover both investment and operating costs of low-carbon investments.

- The State Aid repository shows almost 57 initiatives that can be linked to the CEEAG framework. We identified 9 State Aid approvals that are directly linked to industrial decarbonisation and that cover both investment and operating aid, i.e. using the funding gap concept.
- Only 5 Member States have used the CEEAG to exempt industrials form RES-E support charges, but other EU Member States are expected to follow suit.
- Austria has built the latest example of State Aid framework allowing investment aid, with so-called transition projects, and both investment and operating aid, with so-called 'transformation' projects (see slide 80).
- We have excluded from this analysis the State Aid relative to the EU ETS indirect cost compensation.

Examples of recent State Aid measures approved by the European Commission under the CEEAG framework[1]

Country	Date of approval / End	Name	Description	Sectors	Budget	Type	Investment / Operating aid
Austria (flag)	19/09/2024 – 31/12/2030	Transformation der Industrie: transformation and investment grants under the CEEAG	Support investments in industrial decarbonisation and support for operating costs (energy from renewable sources).	Metallurgy, glass, chemical products, paper, wood and food products	2,732 M€	**Direct grant with competitive bidding process**	**Investment and Operating aid**
France (flag)	07/03/2024 – 31/12/2026	France Aid to ArcelorMittal	Contributing to the steel industry's shift toward climate neutrality by leveraging on the use of low-carbon or renewable H2	Metallurgy	850 M€	**Direct grant to ArcelorMittal France**	**Investment aid**
Italy (flag)	19/12/2023 – 31/12/2033	Reductions of the renewable and cogeneration surcharge for electro-intensive users	Support scheme to compensate electro-intensive users for the electricity charge financing the development of renewables	EIUs with consumption > 1GWh/y	1,400 M€ per year	**Tax exemption**	**Operating aid**

Source: Compass Lexecon analysis based on EC's Competition Policy Repository.
Note: (1) Examples are based on historical data found in the EC's Competition and are not exhaustive.
Abbreviations: H2: Hydrogen; EIU: Electro-Intensive consumer.

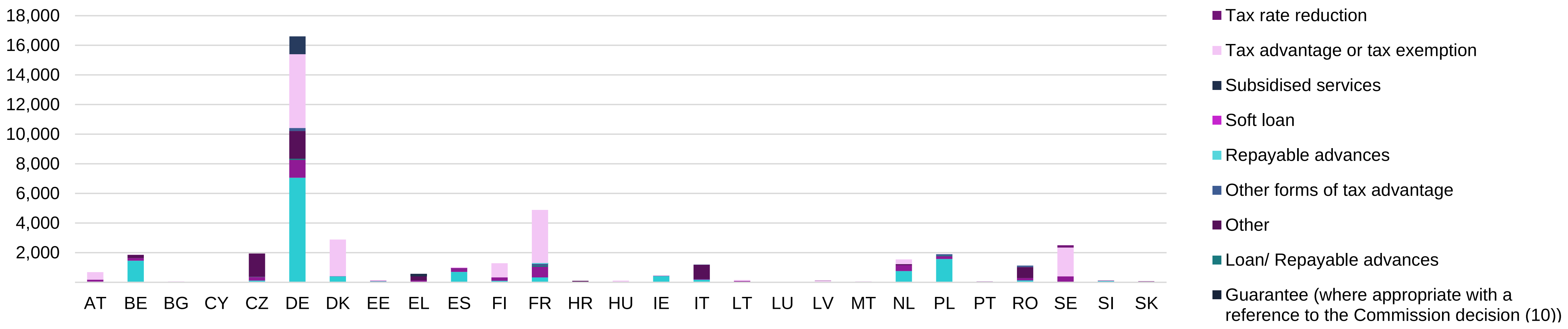
② State Aid for environmental protection

…However, there could be a more coordinated approach for decarbonisation support measures

Relying on State Aid for decarbonising industry runs the risk of seeing the biggest EU Member States decarbonising faster, potentially inducing distortions in the EU internal market. A higher efficiency of decarbonisation measures might be reached with further EU coordination and EU-level schemes.

- Member States have begun using the State Aid framework to cover both investment and operational costs for decarbonisation efforts.
- Different economy sizes between EU Member States impact their ability to grant State Aid.
  - In 2022, Germany accounted for 40% of total State Aid expenditures while France accounted for 12%, largely via green levies exemptions.
  - The aggregate view does not yet reflect the industrial focus of State Aid, but Germany remains the biggest spender, planning to allocate 13bn€ in State Aid for energy-intensive users from 2023 to 2032.

State Aid expenditures under environmental protection measures (including RES-E support) – 2022 (M€)



Source: Compass Lexecon analysis based on EC's Guidelines on State aid for climate, environmental protection and energy 2022; Regulation (EU) 2023/1315; EC's Competition Policy Repository; 2022 data from the EC's Scoreboard State Aid data.
Note: The country name 2-letter abbreviations are based on the ISO 3166-1 alpha-2 codes.

② State Aid for environmental protection

Case study – Austrian and German State Aid schemes under the CEEAG can cover both investment and operating aid

- Launch: 1 December 2024
- Budget: 2.732 bn€ in total until 31 December 2030
- Competitive bidding

Eligibility criteria:

- Sectors: Energy-intensive industries (steel, glass, chemicals, etc.).
- Projects must
  - Reduce GHG emissions by **≥60%** or **≥50 kt CO_2/year**.
  - Use only **renewable energy** and comply with **EU emission standards**.
  - Reference installation must emit ≥10 kt CO_2/year.
  - Compliant with **EU Taxonomy Regulation**.

Aid Mechanism: Aid amounts calculated using the Innovation Fund methodology[1] and linked to EU ETS benchmarks:

1. Investment Grants:

- Covers capital costs (one-time payment).
- **Single payment to** preserve the price signals for operating costs.

2. Transformation Grants:

- Covers capital + operational costs (up to 10 annual payments).

- Launch: Summer 2023 (preparatory procedure)
- Budget: 4 bn€
- Competitive bidding

Eligibility criteria:

- Sectors: Energy-intensive industries under the EU ETS.
- Projects must:
  - Emit **≥10,000 tons CO_2/year**.
  - Achieve **60%** GHG reduction within **3 years** and **90% thereafter**.

Aid Mechanism: Carbon Contracts-for-Difference (CCfD) covering the cost difference between green and conventional production, based on GHG reduction and energy costs:

Aid calculation

- **Basic Agreement Price :** The amount that should cover the additional cost compared to the reference installation, including CAPEX and OPEX
- **Dynamic Agreement Price :** Quantity of energy carrier used per planned tonne of GHG reduction multiplied by the price of energy.

$$(Basic\ Price + Dynamic\ Price - CO_2\ Effective\ Price) \times GHG\ Effective\ Reduction$$

Source: Compass Lexecon analysis based on State Aid SA.109730 (2024/N) – Austria on Transformation der Industrie: transformation and investment grants under the CEEAG (2024); EC's INNOVFUND Methodology for GHG Emission Avoidance Calculation (2024); the German Government's brief on the German CCfD scheme (2023) and its draft guidelines.

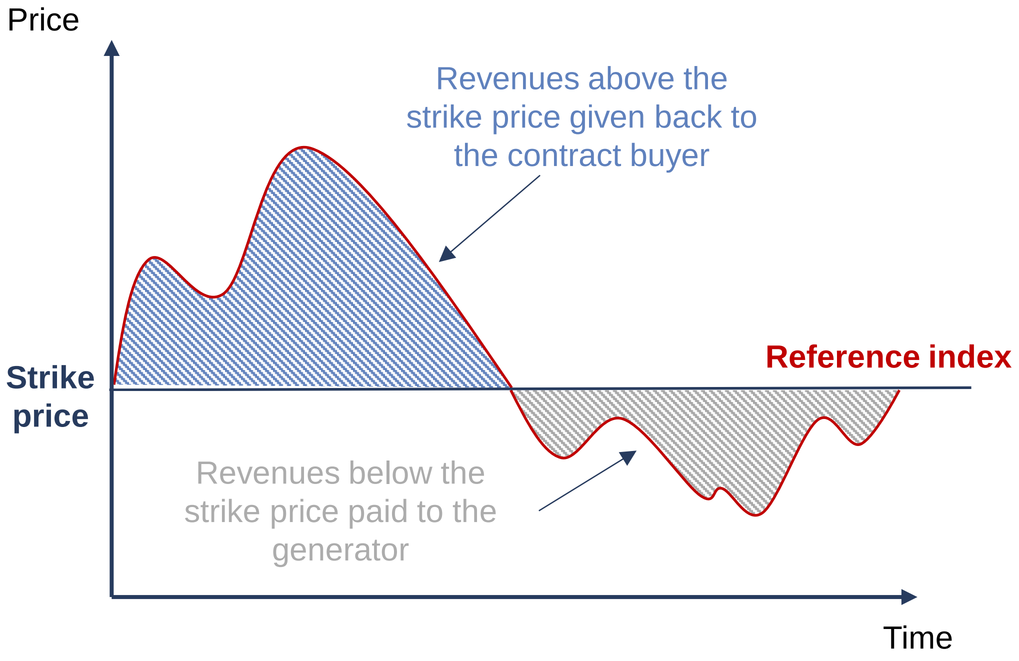
② State Aid for environmental protection

Case study – Contracts-for-difference could be a useful support mechanism for industries that opt for a switch to electricity supply

Two-sided Contracts for Difference (CfDs) are an appropriate model to support industrial decarbonisation.

- While CfDs are traditionally associated with electricity generation, they could potentially be adapted for industrial end-users or decarbonisation in energy-intensive sectors through electrification and low-carbon technologies.
- Contracts-for-difference (CfDs) are long-term contracts with an electricity generator, where the buyer (such as industrials) pays the contractual 'strike' price to the seller (in practice, RES or low carbon generator) for the contracted volume, and the seller pays the reference index to the buyer.
- Several energy providers already structure corporate PPA-style CfDs for industrial end-users, offering fixed-price electricity from renewable sources.
- Governments could expand CfDs to industry, subsidising renewable electricity for industrial end-users while ensuring that industries reduce their carbon footprint.
- Fostering access to CfDs for renewable electricity procurement could provide price stability to large electro-intensive users and shield them from highly volatile prices while providing visibility on returns for suppliers.

Illustration of the functioning of the CfD



Source: Compass Lexecon analysis.

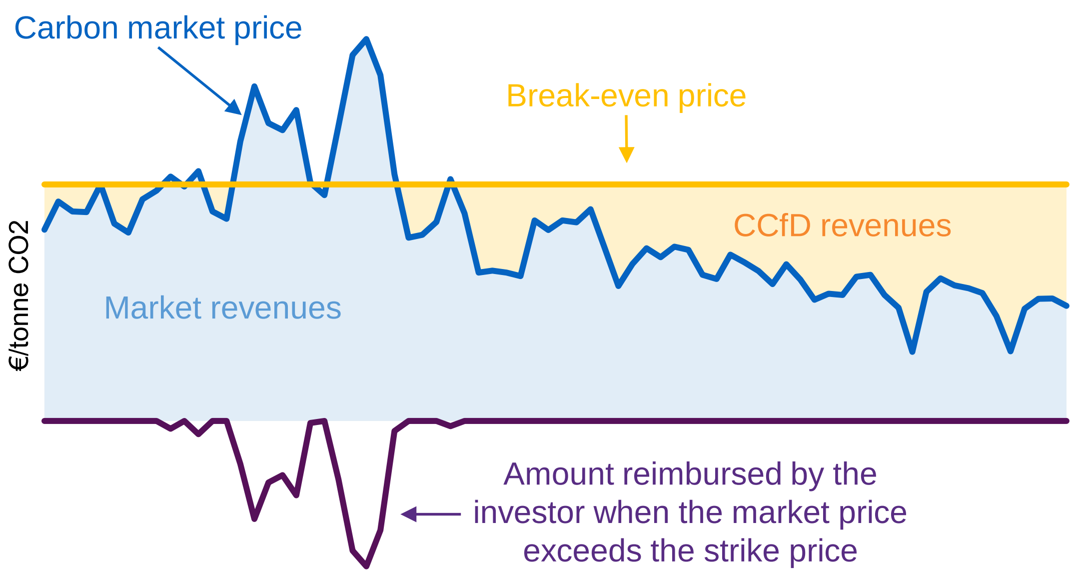
② State Aid for environmental protection

Case study – Carbon contracts-for-difference are an innovative way to compensate the funding gap and encourage industrial decarbonisation

A CCfD mitigates regulatory risks for private investors by providing longer-term certainty on the value of abating emissions.

- Currently, technologies capable of decarbonising the industry are financially viable only at carbon price levels significantly higher than today's price levels. As a result, these investments are not pursued, delaying technological cost reductions.
- The purpose of CCfDs is to bridge the gap between current carbon prices and the levels needed to trigger investment. In a CCfD scheme, governments support project financing by compensating the difference between the break-even carbon price and the traded carbon price. Conversely, if market prices exceed the break-even price, the investor reimburses the government.
- For each CCfD, a number of key design parameters are to be defined, such as indexation to inflation, payment thresholds, contract length, and regular reviews.
- Notably, a contract similar to a CCfD has been awarded in the Netherlands and the German government has launched a CCfD program. And the EC has included CCfDs in the Fit-for-55 reform as a novel mean to distribute revenues from the Innovation Fund.

Illustration of the functioning of the CCfD



Source: Compass Lexecon analysis.

② State Aid for environmental protection

Carbon contracts-for-differences could be an efficient way to use State Aid but raise implementation challenges

- CCfDs could be an attractive policy tool for driving industrial decarbonisation and scaling up low-carbon technologies, with its fundamental principles being on creating market-based incentives that would bridge the investment gap and accelerate technological deployment.
- However, their complexity necessitates cautious planning, robust governance frameworks, and adaptive mechanisms to address uncertainties and ensure their effectiveness over time.

CCfDs could be an efficient way to support industrial decarbonisation by linking the Aid disbursement with the evolution of market conditions for the EUA price, which could:

- ☑ Efficiently "de-risk" projects that require major investments by sharing the risk with the chosen counterparty
- ☑ Accelerate the development of technologies that are not currently competitive but are of interest to carbon-intensive sectors
- ☑ Limit risks of overcompensation for governments leading to a reduced fiscal commitment compared to subsidies
- ☑ Limit risks of carbon leakage to a certain extent

CCfDs are considered a complex policy instrument raising several challenges with decisions still to be finalised regarding their design, implementation and management, such as:

- ? Risk allocation and financial exposure between the governments and private actors
- ? Duration of support, targeted technologies and adequation with the learning curves to avoid unnecessary support
- ? Compatibility with State Aid as it confers advantages on a selective basis, and design of the tenders
- ? Geographical scope (European or national level)

Source: Compass Lexecon analysis based on The Climate Friendly Materials (CFM) Platform's Carbon Contracts for Differences Policy Brief (2020); The Institute for Sustainable Development and International Relations (IDDRI)'s Study N°06/19 on How Carbon Contracts-for-Difference could help bring breakthrough technologies to market.

3 Snapshot on EU Funds

At least five different funds can provide investment support to industrial manufacturing sectors seeking to switch to low-carbon processes at EU level…

EU Funds	Total fund size	Targets
Innovation Fund	40 bn€ for 2020-2030	▪ Key funding instrument to deliver EU's commitment under, among others, the Paris Agreement, REPowerEU, Green Deal Industrial Plan and Net-Zero Industry Act. ▪ To foster net-zero and innovative technologies, including **manufacturing and production in energy intensive industries.** ▪ Call for proposals in 2023 included a budget of **1 bn€ for innovative electrification in industry and hydrogen.** ▪ However, the overall funding requests received in 2023 revealed a large **funding gap** with a funding request of 24.6 bn€ against a total available yearly budget of 4 bn€.
Horizon Europe	93.5 bn€ for 2021-2027	▪ EU framework programme for research and innovation funding. ▪ Among others, aiming to support industrial competitiveness and economic growth in the EU, including **industry transition towards climate neutrality.** ▪ Cluster 4 'Digital, Industry and Space' included an indicative budget of **35.67 M€ for electrification of high temperature heating systems** in the work programme for 2023-2025.
Recovery and Resilience Facility	724 bn€	▪ Aims to finance reforms and investments in Member States made from the start of the Covid pandemic in 2020 until 2026. ▪ Support requires Member States to submit national Recovery and Resilience Plans (RRP) incl. planned reforms and investments with clear milestones and targets. ▪ At least 37% of the budget should be allocated to **green measures** and 20% to digital measures. ▪ RRPs of 21 Member States include measures of **direct support to companies with more than 47 bn€** until 2026.
Just Transition Fund	19.2 bn€ for 2021-2027	▪ Aims to mitigate economic and social consequences of, among others, the energy transition and to support the diversification and transition of territories, industries and workers most dependent on fossil fuels. ▪ Support can be provided to e.g., productive investments in SMEs, upskilling and reskilling of workers and **transformation of existing carbon-intensive installations** when these investments lead to substantial emission cuts and job protection.
Modernisation Fund	57 bn€ for 2021-2030	▪ Supporting the modernisation of energy systems and improvement of **energy efficiency, including in industry**, in lower-income Member States.

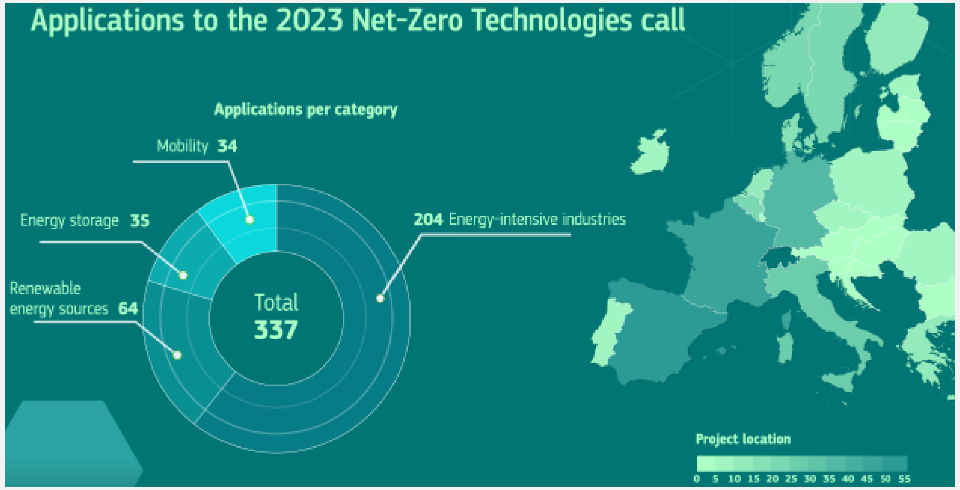
Source: Compass Lexecon analysis based on BusinessEurope's study on Energy and climate transition: How to strengthen the EU's competitiveness (2024).
Note: This list of EU funds is not exhaustive. Other notable funds include the Connecting Europe Facility (CEF) Fund and the Cohesion Fund (CF).

③ Snapshot on EU Funds

… But funding needs could significantly exceed available funding as of today: example of the IF23 call

The Innovation Fund 2023 call for proposal has received 337 applications from all EU countries, with regional disparities.

- Most of the applications come from Western and Central Europe, with Spain, France and Germany representing the majority of the applications.



*The Innovation Fund is an example of a funding gap, but the same issue also appears with **other EU instruments** (CEF-E, InvestEU, etc.).*

The total funding requested vastly exceeds the available budget.

- The funding call was 5 times oversubscribed, with applications worth more than 20 bn€ having to be turned down.

Total funding requested | **Available budget**

The timeline raises questions.

- The call was launched in November 2023, with a deadline in April 2024.
- Applicants will be informed of the results in Q4 2024 and funding will be available in Q1 2025.
- Given the recent increase in decarbonisation objectives and the pressure on EU competitiveness, the timeline could have been shortened, with more than one year between the call and the availability of the funds.

Source: Compass Lexecon analysis based on EC's article on Innovation Fund: Overwhelming response to the 2023 net-zero technologies call (2024); BusinessEurope's study on Energy and climate transition: How to strengthen the EU's competitiveness (2024).

CONTACT

Fabien Roques

Head of European Energy Practice

froques@compasslexecon.com

Florian Bourcier

Senior Economist

fbourcier@compasslexecon.com

Acknowledgements

- Compass Lexecon appreciates the scientific contributions and valuable inputs provided by Enel Foundation, the European Roundtable on Climate Change and Sustainable Transition (ERCST) and the different organisations who participated in the stakeholder consultations and other exchanges.
- This report was authored by Fabien Roques, Florian Bourcier, Peter Chawah and Keyvan Rucheton.

Berlin
Kurfürstendamm 217
Berlin, 10719

Brussels
23 Square de Meeûs
Brussels, 1000

Copenhagen
Bredgade 6
Copenhagen, 1260

Düsseldorf
Kö-Bogen, Königsallee 2B
Düsseldorf, 40212

Helsinki
Unioninkatu 30
Helsinki, 00100

Lisbon
Praça Marquês de Pombal 14
Lisboa, 1250-162

London
5 Aldermanbury Square
London, EC2V 7HR

Madrid
Paseo de la Castellana 7
Madrid, 28046

Milan
Via San Raffaele 1
Milan, 20121

Paris
22 Place de la Madeleine
Paris, 75008

COMPASS LEXECON

List of contributors to the stakeholders’ consultations

AB Lifosa (EuroChem)
AFEP
Air Liquide
BDI
Bruegel
Cefic
CEMBUREAU
Cepi
Cerame-Unie
Confindustria
Dow Europe GmbH
EDF
Eurelectric
Eurofer
Eurometaux
European Aluminium
Fertilizers Europe
FoodDrinkEurope
FuelsEurope
Glass for Europe
HELLENiQ ENERGY
Hydro
Hydrogen Europe
Ineos
JSC Lifosa (EuroChem)
Metlen
Orgalim
Plastics Europe
Yara

Compass Lexecon, ENEL Foundation and the ERCST would like to thank all the organizations that took part in the consultation meetings and the written consultation for their constructive exchanges and detailed contributions which helped refine the scope and assumptions of the study. The views expressed in this report are those of the authors only and any potential inaccuracies remaining in the analysis entirely their own.

A.

Appendix

A.1 Focus on barriers to industrial electrification

Barriers to industrial electrification – Economic barriers

Economic barriers	Food & Beverages	Paper & Pulp	Chemicals (Low °T)	Chemicals (High °T)	Iron & Steel	Aluminium	Glass	Cement
CAPEX								
High up-front investment costs	X *(heat pumps)*	X *(heat pumps)*	X *(heat pumps)*	X	X	X	X	X
High retrofitting and infrastructure costs	X	X	X	X	X	X	X	X
OPEX								
High electricity-to-gas price ratio	X *(COP-dependent for heat pumps)*	X *(COP-dependent for heat pumps)*	X *(COP-dependent for heat pumps)*	X	X	X	X	X
High green hydrogen costs				X	X	X	X	X
High price volatility	X *(COP-dependent for heat pumps)*	X *(COP-dependent for heat pumps)*	X *(COP-dependent for heat pumps)*	X	X	X	X	X
Increase in raw material supply costs due to low-carbon origins		X		X	X	X		X
Investment cycle								
Prolonged period of production halt			X	X	X	X	X	X
Long investment cycles and risk of stranded assets	X	X			X	X	X	X
Risk of carbon intensive process lock-in due to lack of mature cost-efficient decarbonisation technologies					X	X	X	X

Low barrier **High barrier**

Source: Compass Lexecon analysis based on sectoral decarbonisation roadmaps; inputs from industry representatives during the consultation process of the project; literature review.
Note: The list of barriers is not exhaustive.

Barriers to industrial electrification – Technological barriers

Technological barriers	Food & Beverages	Paper & Pulp	Chemicals (Low °T)	Chemicals (High °T)	Iron & Steel	Aluminium	Glass	Cement
Technological properties								
High temperature and pressure process requirements				X	X	X *(several processes already electrified)*	X	X
High production volume and energy requirements				X	X	X	X	X
Lack of availability of mature electrification solutions (low TRL)			X *(only for coke and refinery products)*	X	X *(EAF used for secondary steel)*	X *(several processes already electrified)*	X *(electric boost systems available)*	X
Logistical challenges in raw material and energy supply				X *(structural global value chains)*	X *(low availability of scrap)*	X *(low availability of recyclables)*	X	X *(low availability of low-carbon waste)*

Low barrier **High barrier**

Source: Compass Lexecon analysis based on sectoral decarbonisation roadmaps; inputs from industry representatives during the consultation process of the project; literature review.
Note: The list of barriers is not exhaustive.

Barriers to industrial electrification – Infrastructure barriers

Infrastructure barriers	Food & Beverages	Paper & Pulp	Chemicals (Low °T)	Chemicals (High °T)	Iron & Steel	Aluminium	Glass	Cement
Network infrastructure								
Lack of coordination between electrification and network development plans	X	X	X	X	X	X	X	X
Insufficient electricity grid capacity				X	X	X	X	X
Electricity grid connection delays due to long permitting processes and large connection queues				X	X	X	X	X
Congestion issues and localised constraints	X	X	X	X	X	X	X	X
Lack of availability and/or proximity of connection points	X	X	X	X	X	X	X	X
Limited interconnection capacity				X	X	X	X	X
Lack of readiness of hydrogen network infrastructure and sufficient capacity				X	X	X	X	X

Low barrier **High barrier**

Source: Compass Lexecon analysis based on sectoral decarbonisation roadmaps; inputs from industry representatives during the consultation process of the project; literature review.
Note: The list of barriers is not exhaustive.

Barriers to industrial electrification – Regulatory barriers

Regulatory barriers	Food & Beverages	Paper & Pulp	Chemicals (Low °T)	Chemicals (High °T)	Iron & Steel	Aluminium	Glass	Cement
Regulatory framework								
Stringent product quality and compliance standards	X	X	X					
Stringent climate and environmental regulations and emission standards	X	X	X	X	X	X	X	X
Lack of adequate support framework, including dedicated CAPEX funding support	X	X	X	X	X	X	X	X
Lack of a realistic anti-carbon leakage and post-2030 EU ETS framework				X	X	X	X	X
Lack of adequate permitting processes as well as integration provisions					X			X
Regulatory stability								
Uncertainty regarding the evolutions of environmental standards and compliance requirements	X	X	X	X	X	X	X	X
Uncertainty on the status of biogas, biomass and/or renewable waste as "renewable"		X	X					X
Uncertainty regarding EU ETS evolutions				X	X	X	X	X

Low barrier **High barrier**

Source: Compass Lexecon analysis based on sectoral decarbonisation roadmaps; inputs from industry representatives during the consultation process of the project; literature review.
Note: The list of barriers is not exhaustive.

Barriers to industrial electrification – Supply chain barriers

Supply chain barriers	Food & Beverages	Paper & Pulp	Chemicals (Low °T)	Chemicals (High °T)	Iron & Steel	Aluminium	Glass	Cement
Labour force								
General shortage of skilled labour	X	X	X	X	X	X	X	X
Input supply								
Electricity security of supply risks				X	X	X	X	X
Lack of available and affordable renewable electricity	X	X	X	X	X	X	X	X
Lack of available and affordable green hydrogen				X	X	X	X	X
Lack of available and suitable low-carbon inputs		X	X	X	X	X		X

Low barrier **High barrier**

Source: Compass Lexecon analysis based on sectoral decarbonisation roadmaps; inputs from industry representatives during the consultation process of the project; literature review.
Note: The list of barriers is not exhaustive.

Barriers to industrial electrification – Structural barriers

Structural barriers	Food & Beverages	Paper & Pulp	Chemicals (Low °T)	Chemicals (High °T)	Iron & Steel	Aluminium	Glass	Cement
Company size								
Large size as potential issue due to higher energy requirements	X	X	X	X	X	X	X	X
Small size as potential issue due to risk of limited adaptability (access to information, limited portfolio / skills)			X	X				
Company location								
Risk of long distance from available (low-carbon) energy infrastructure	X	X	X	X	X	X	X	X
Lack of available suitable low-carbon inputs		X	X	X	X	X	X	X
Risk of higher input and energy prices	X	X	X	X	X	X	X	X

Low barrier — **High barrier**

Source: Compass Lexecon analysis based on sectoral decarbonisation roadmaps; inputs from industry representatives during the consultation process of the project; literature review.
Note: The list of barriers is not exhaustive.

A.2 Sectoral decarbonisation roadmaps, and carbon leakage indicator per manufacturing activity under EU NACE 2 Codes

Most decarbonisation roadmaps of manufacturing industries highlight that, under the right conditions, deep decarbonisation can be achieved (1/2)

Sector	Author/involved association	Achievable decarbonisation in 2050	Conditions to achieve decarbonisation
Food and beverages	FoodDrinkEurope (2021), link	• 92% in the best-case scenario compared to 1990 levels. • 47%. For the worst-case scenario only	▪ Assessment of cost effectiveness in adopting low-carbon ▪ Policy framework to facilitate and regulate investments, support innovation and give incentive ▪ Increasing the use of sustainable biomass and (carbon-free) electrification of processes
Paper and pulp	Cepi (2021), link	• Net-zero	▪ Commercial availability of emerging and breakthrough technologies ▪ De-risking or risk-sharing tools and improved conditions for accessing finance, including for research and development ▪ Facilitate the production of renewable energy on site ▪ Promote industrial symbiosis and energy system integration
Chemicals	Cefic (2024), link	• Not specified	▪ Availability and supplies of abundant renewable energy ▪ Creating demand and markets for low-carbon products ▪ Support from a research and innovation (R&I) policy agenda
	European Commission, (2023), link	• Not specified	▪ Development of chain-of-custody principles to finance the extra cost of sustainable feedstocks and energy ▪ Effective and predictable legislation based on definitions, concepts and methodologies jointly agreed by policymakers and industry. ▪ Secure the chemical industry's access to energy and feedstock
Plastics	Plastics Europe (2023), link	• Net-zero	▪ Availability of circular feedstock ▪ Incentives for demand and investments for circular solutions (standardised sustainability assessment tools, regulations…) ▪ Access to low-carbon energy, hydrogen and biofuels

Source: Compass Lexecon analysis.

Most decarbonisation roadmaps of manufacturing industries highlight that, under the right conditions, deep decarbonisation can be achieved (2/2)

Sector	Author/involved association	Achievable decarbonisation in 2050	Conditions to achieve decarbonisation
Non-metallic minerals Cement and concrete	Cembureau (2024), link	• 115% compared to 1990 (due to CCUS)	• Access to affordable decarbonised energy, infrastructure and raw materials • Financing to de-risk the full CCUS value chain • Scale up to industrial scale the development and production of these new types of cement clinker
Non-metallic minerals Ceramics	Cerame-unie (2021), link	• Net-zero	• Financial support both for research and innovation, for investments, and to mitigate higher running operational costs • Secure infrastructure and a stable supply of green energy • Carbon price incentivising investments
Non-metallic minerals Flat glass	Glass for Europe (2020), link	• Net-zero	• The guaranteed supply of carbon-free electricity and biogas • Carbon capture transport net-works and storage facilities. • Waste management facilities to collect and recycle end-of-life building glass • R&D efforts need to be stimulated and better supported in Europe • Adequate competitiveness mitigation • New legislative packages to promote a circular economy, an EU ETS that is robust against carbon leakage, hydrogen and a zero-carbon electricity industry.
Metallurgy Steel	Eurofer (2019), link	• 80-95% in 2050 compared to 1990 levels	• Access to sufficient low-CO2 energy and raw materials • A mature Carbon Capture and Storage (CCS) technology • A regulatory framework that ensures that the EU steel industry remains competitive
Metallurgy Aluminium	Aluminium Europe (2023), link	• more than 90%	• Prioritise and increase investments in R&D for low-carbon technologies • Accelerate the decarbonisation of power generation at a competitive price • Increase scrap recovery and recycling • Incentivise and support European low-carbon and circular production capacity.

Source: Compass Lexecon analysis.

Trade and carbon indicators per sub industrial sectors grouping following EU NACE 2 codes and EU ETS phase 4 : Food & Beverages

Compass Lexecon analysis based on grouping	NACE 2 code Level 2	NACE 2 code Level 3	Trade intensity	Emission intensity (kg CO2 / €)	Carbon Leakage Indicator
Food & Beverage	Manufacture of food products	Processing and preserving of meat	0.131	0.23	0.03
Food & Beverage	Manufacture of food products	Processing and preserving of poultry meat	0.065	0.271	0.018
Food & Beverage	Manufacture of food products	Production of meat and poultry meat products	0.054	0.171	0.009
Food & Beverage	Manufacture of food products	Processing and preserving of fish, crustaceans and molluscs	0.445	0.165	0.074
Food & Beverage	Manufacture of food products	Processing and preserving of potatoes	0.122	0.667	0.081
Food & Beverage	Manufacture of food products	Manufacture of fruit and vegetable juice	0.251	0.35	0.088
Food & Beverage	Manufacture of food products	Other processing and preserving of fruit and vegetables	0.255	0.327	0.083
Food & Beverage	Manufacture of food products	Manufacture of oils and fats	0.434	0.965	0.419
Food & Beverage	Manufacture of food products	Manufacture of margarine and similar edible fats	0.149	0.2	0.03
Food & Beverage	Manufacture of food products	Operation of dairies and cheese making	0.106	0.397	0.042
Food & Beverage	Manufacture of food products	Manufacture of ice cream	0.05	0.233	0.012
Food & Beverage	Manufacture of food products	Manufacture of grain mill products	0.102	0.371	0.038
Food & Beverage	Manufacture of food products	Manufacture of starches and starch products	0.185	2796	0.515
Food & Beverage	Manufacture of food products	Manufacture of bread; manufacture of fresh pastry goods and cakes	0.012	0.078	0.001
Food & Beverage	Manufacture of food products	Manufacture of rusks and biscuits; manufacture of preserved pastry goods and cakes	0.116	0.167	0.019
Food & Beverage	Manufacture of food products	Manufacture of macaroni, noodles, couscous and similar farinaceous products	0.152	0.232	0.035
Food & Beverage	Manufacture of food products	Manufacture of sugar	0.197	3208	0.63
Food & Beverage	Manufacture of food products	Manufacture of cocoa, chocolate and sugar confectionery	0.215	0.154	0.033
Food & Beverage	Manufacture of food products	Processing of tea and coffee	0.227	0.161	0.037
Food & Beverage	Manufacture of food products	Manufacture of condiments and seasonings	0.174	0.098	0.017
Food & Beverage	Manufacture of food products	Manufacture of prepared meals and dishes	0.202	0.233	0.047
Food & Beverage	Manufacture of food products	Manufacture of homogenised food preparations and dietetic food	0.578	0.186	0.107
Food & Beverage	Manufacture of food products	Manufacture of other food products N.E.C.	0.216	0.206	0.044
Food & Beverage	Manufacture of food products	Manufacture of prepared feeds for farm animals	0.048	0.395	0.019
Food & Beverage	Manufacture of food products	Manufacture of prepared pet foods	0.116	0.18	0.021
Food & Beverage	Manufacture of beverage	Distilling, rectifying and blending of spirits	0.652	0.108	0.071
Food & Beverage	Manufacture of beverage	Manufacture of wine from grape	0.387	0.043	0.017
Food & Beverage	Manufacture of beverage	Manufacture of cider and other fruit wines	0.091	0.117	0.011
Food & Beverage	Manufacture of beverage	Manufacture of other non-distilled fermented beverages	0.259	0.42	0.109
Food & Beverage	Manufacture of beverage	Manufacture of beer	0.106	0.169	0.018
Food & Beverage	Manufacture of beverage	Manufacture of malt	0.327	1022	0.333
Food & Beverage	Manufacture of beverage	Manufacture of soft drinks; production of mineral waters and other bottled waters	0.079	0.178	0.014

Source: Compass Lexecon analysis based on EU's Carbon Leakage Regulation
Note: The sub-sectors considered here are based on the EU's NACE 2 codes. For further details, please refer to the appendix.
Note: Trade intensity is calculated as the sum of imports and exports divided by the sum of turnover and imports; the average of each sector was weighted by the value of each sub-sector application. Emission intensity is the sum of the direct and indirect emission intensity (DEI and IEI) in kg CO_2/€, with the DEI (IEI) being the ratio between direct (indirect) emissions and the GVA entire sector's direct (indirect) emissions, the average of each sector was weighted by the value of each sub-sector application. The carbon leakage indicator is the product of the trade intensity and the emission intensity.

Trade and carbon indicators per sub industrial sectors grouping following EU NACE 2 codes and EU ETS phase 4 : Paper & Pulp and Plastics

Compass Lexecon analysis based on grouping	NACE 2 code Level 2	NACE 2 code Level 3	Trade intensity	Emission intensity (kg CO2 / €)	Carbon Leakage Indicator
Paper & Pulp	Manufacture of paper and paper products	Manufacture of pulp	0.481	2054	0.987
Paper & Pulp	Manufacture of paper and paper products	Manufacture of paper and paperboard	0.278	3010	0.836
Paper & Pulp	Manufacture of paper and paper products	Manufacture of corrugated paper and paperboard and of containers of paper and paperboard	0.06	0.19	0.011
Paper & Pulp	Manufacture of paper and paper products	Manufacture of household and sanitary goods and of toilet requisites	0.161	0.504	0.081
Paper & Pulp	Manufacture of paper and paper products	Manufacture of paper stationery	0.165	0.132	0.022
Paper & Pulp	Manufacture of paper and paper products	Manufacture of wallpaper	0.51	0.211	0.109
Paper & Pulp	Manufacture of paper and paper products	Manufacture of other articles of paper and paperboard	0.14	0.13	0.018
Plastics	Manufacture of rubber and plastic products	Manufacture of rubber tyres and tubes; retreading and rebuilding of rubber tyres	0.474	0.255	0.121
Plastics	Manufacture of rubber and plastic products	Manufacture of other rubber products	0.377	0.172	0.065
Plastics	Manufacture of rubber and plastic products	Manufacture of plastic plates, sheets, tubes and profiles	0.257	0.305	0.078
Plastics	Manufacture of rubber and plastic products	Manufacture of plastic packing goods	0.155	0.405	0.063
Plastics	Manufacture of rubber and plastic products	Manufacture of builders' ware of plastic	0.126	0.086	0.011
Plastics	Manufacture of rubber and plastic products	Manufacture of other plastic products	0.241	0.194	0.047
Plastics	Manufacture of rubber and plastic products	Manufacture of plastics in primary forms	0.36	0.867	0.312

Source: Compass Lexecon analysis based on EU's Carbon Leakage Regulation
Note: The sub-sectors considered here are based on the EU's NACE 2 codes. For further details, please refer to the appendix.
Note: Trade intensity is calculated as the sum of imports and exports divided by the sum of turnover and imports; the average of each sector was weighted by the value of each sub-sector application. Emission intensity is the sum of the direct and indirect emission intensity (DEI and IEI) in kg CO_2/€, with the DEI (IEI) being the ratio between direct (indirect) emissions and the GVA entire sector's direct (indirect) emissions, the average of each sector was weighted by the value of each sub-sector application. The carbon leakage indicator is the product of the trade intensity and the emission intensity.

Trade and carbon indicators per sub industrial sectors grouping following EU NACE 2 codes and EU ETS phase 4 : Chemicals and Petrochemicals

Compass Lexecon analysis based on grouping	NACE 2 code Level 2	NACE 2 code Level 3	Trade intensity	Emission intensity (kg CO2 / €)	Carbon Leakage Indicator
Chemicals and Petrochemicals (High temperature)	Manufacture of coke and refined petroleum products	Manufacture of coke oven products	1.089	18284	20119
Chemicals and Petrochemicals (High temperature)	Manufacture of coke and refined petroleum products	Manufacture of refined petroleum products	0.258	12471	3222
Chemicals and Petrochemicals (High temperature)	Manufacture of chemicals and chemical products	Manufacture of industrial gases	0.06	16819	1021
Chemicals and Petrochemicals (High temperature)	Manufacture of chemicals and chemical products	Manufacture of dyes and pigments	0.485	1070	0.519
Chemicals and Petrochemicals (High temperature)	Manufacture of chemicals and chemical products	Manufacture of other inorganic basic chemicals	0.54	3038	1638
Chemicals and Petrochemicals (High temperature)	Manufacture of chemicals and chemical products	Manufacture of other organic basic chemicals	0.49	2153	1049
Chemicals and Petrochemicals (High temperature)	Manufacture of chemicals and chemical products	Manufacture of fertilisers and nitrogen compounds	0.318	7636	2418
Chemicals and Petrochemicals (High temperature)	Manufacture of chemicals and chemical products	Manufacture of plastics in primary forms	0.36	0.867	0.312
Chemicals and Petrochemicals (High temperature)	Manufacture of chemicals and chemical products	Manufacture of synthetic rubber in primary forms	0.551	1096	0.604
Chemicals and Petrochemicals Low temperature)	Manufacture of chemicals and chemical products	Manufacture of pesticides and other agrochemical products	0.556	0.159	0.089
Chemicals and Petrochemicals Low temperature)	Manufacture of chemicals and chemical products	Manufacture of paints, varnishes and similar coatings, printing ink and mastics	0.27	0.103	0.028
Chemicals and Petrochemicals Low temperature)	Manufacture of chemicals and chemical products	Manufacture of soap and detergents, cleaning and polishing preparations	0.26	0.108	0.028
Chemicals and Petrochemicals Low temperature)	Manufacture of chemicals and chemical products	Manufacture of perfumes and toilet preparations	0.657	0.054	0.035
Chemicals and Petrochemicals Low temperature)	Manufacture of chemicals and chemical products	Manufacture of explosives	0.274	0.177	0.048
Chemicals and Petrochemicals Low temperature)	Manufacture of chemicals and chemical products	Manufacture of glues	0.304	0.22	0.067
Chemicals and Petrochemicals Low temperature)	Manufacture of chemicals and chemical products	Manufacture of essential oils	0.863	0.054	0.046
Chemicals and Petrochemicals Low temperature)	Manufacture of chemicals and chemical products	Manufacture of other chemical products N.E.C.	0.58	0.254	0.147
Chemicals and Petrochemicals (High temperature)	Manufacture of chemicals and chemical products	Manufacture of man-made fibres	0.441	0.933	0.412
Chemicals and Petrochemicals Low temperature)	Manufacture of basic pharmaceutical products and pharmaceutical preparations	Manufacture of basic pharmaceutical products	0.886	0.216	0.192
Chemicals and Petrochemicals Low temperature)	Manufacture of basic pharmaceutical products and pharmaceutical preparations	Manufacture of pharmaceutical preparations	1.089	18284	20119

Source: Compass Lexecon analysis based on EU's Carbon Leakage Regulation
Note: The sub-sectors considered here are based on the EU's NACE 2 codes. For further details, please refer to the appendix.
Note: Trade intensity is calculated as the sum of imports and exports divided by the sum of turnover and imports; the average of each sector was weighted by the value of each sub-sector application. Emission intensity is the sum of the direct and indirect emission intensity (DEI and IEI) in kg CO_2/€, with the DEI (IEI) being the ratio between direct (indirect) emissions and the GVA entire sector's direct (indirect) emissions, the average of each sector was weighted by the value of each sub-sector application. The carbon leakage indicator is the product of the trade intensity and the emission intensity.

Trade and carbon indicators per sub industrial sectors grouping following EU NACE 2 codes and EU ETS phase 4 : Iron & Steel, Aluminium and Other non-ferrous metals

Compass Lexecon analysis based on grouping	NACE 2 code Level 2	NACE 2 code Level 3	Trade intensity	Emission intensity (kg CO2 / €)	Carbon Leakage Indicator
Iron & Steel (Metallurgy)	Manufacture of basic metals	Manufacture of basic iron and steel and of ferro-alloys	0.257	8273	2121
Iron & Steel (Metallurgy)	Manufacture of basic metals	Manufacture of tubes, pipes, hollow profiles and related fittings, of steel	0.485	0.473	0.229
Iron & Steel (Metallurgy)	Manufacture of basic metals	Cold drawing of bars	0.37	0.707	0.259
Iron & Steel (Metallurgy)	Manufacture of basic metals	Cold rolling of narrow strip	0.136	0.422	0.058
Iron & Steel (Metallurgy)	Manufacture of basic metals	Cold forming or folding	0.086	0.151	0.013
Iron & Steel (Metallurgy)	Manufacture of basic metals	Cold drawing of wire	0.266	0.507	0.135
Iron & Steel (Metallurgy)	Manufacture of basic metals	Casting of iron	0.41	1191	0.488
Iron & Steel (Metallurgy)	Manufacture of basic metals	Casting of steel	0.043	0.402	0.017
Iron & Steel (Metallurgy)	Manufacture of basic metals	Casting of light metals	0.043	0.415	0.018
Aluminium (Non-ferrous metals)	Manufacture of basic metals	Aluminium production	0.352	4629	1632
Other non-ferrous metals	Manufacture of basic metals	Precious metals production	0.909	0.101	0.092
Other non-ferrous metals	Manufacture of basic metals	Lead, zinc and tin production	0.306	3367	1031
Other non-ferrous metals	Manufacture of basic metals	Copper production	0.351	1199	0.421
Other non-ferrous metals	Manufacture of basic metals	Other non-ferrous metal production	0.835	0.335	0.28
Other non-ferrous metals	Manufacture of basic metals	Processing of nuclear fuel	0.363	0.592	0.215
Other non-ferrous metals	Manufacture of basic metals	Casting of other non-ferrous metals	0.043	0.214	0.009

Source: Compass Lexecon analysis based on EU's Carbon Leakage Regulation
Note: The sub-sectors considered here are based on the EU's NACE 2 codes. For further details, please refer to the appendix.
Note: Trade intensity is calculated as the sum of imports and exports divided by the sum of turnover and imports; the average of each sector was weighted by the value of each sub-sector application. Emission intensity is the sum of the direct and indirect emission intensity (DEI and IEI) in kg CO_2/€, with the DEI (IEI) being the ratio between direct (indirect) emissions and the GVA entire sector's direct (indirect) emissions, the average of each sector was weighted by the value of each sub-sector application. The carbon leakage indicator is the product of the trade intensity and the emission intensity.

Trade and carbon indicators per sub industrial sectors grouping following EU NACE 2 codes and EU ETS phase 4 : Glass, Cement and Other non-metallic mineral products

Compass Lexecon analysis based on grouping	NACE 2 code Level 2	NACE 2 code Level 3	Trade intensity	Emission intensity [kg CO2 / €]	Carbon Leakage Indicator
Glass	**Manufacture of other non-metallic mineral products**	Manufacture of flat glass	0.043	0.214	0.009
Glass	**Manufacture of other non-metallic mineral products**	Shaping and processing of flat glass	0.237	6091	1457
Glass	**Manufacture of other non-metallic mineral products**	Manufacture of hollow glass	0.206	0.322	0.066
Glass	**Manufacture of other non-metallic mineral products**	Manufacture of glass fibres	0.247	2554	0.631
Glass	**Manufacture of other non-metallic mineral products**	Manufacture and processing of other glass, including technical glassware	0.284	1467	0.417
Cement	**Manufacture of other non-metallic mineral products**	Manufacture of cement	0.485	0.471	0.228
Cement	**Manufacture of other non-metallic mineral products**	Manufacture of concrete products for construction purposes	0.101	24221	2455
Cement	**Manufacture of other non-metallic mineral products**	Manufacture of ready-mixed concrete	0.038	0.078	0.003
Cement	**Manufacture of other non-metallic mineral products**	Manufacture of fibre cement	0.068	0.741	0.051
Cement	**Manufacture of other non-metallic mineral products**	Manufacture of other articles of concrete, plaster and cement	0.001	0.063	0
Other non-metallic mineral products	**Manufacture of other non-metallic mineral products**	Manufacture of plaster products for construction purposes	0.033	0.12	0.004
Other non-metallic mineral products	**Manufacture of other non-metallic mineral products**	Manufacture of mortars	0.119	0.249	0.03
Other non-metallic mineral products	**Manufacture of other non-metallic mineral products**	Manufacture of refractory products	0.097	0.092	0.009
Other non-metallic mineral products	**Manufacture of other non-metallic mineral products**	Manufacture of ceramic tiles and flags	0.442	0.929	0.412
Other non-metallic mineral products	**Manufacture of other non-metallic mineral products**	Manufacture of bricks, tiles and construction products, in baked clay	0.411	2550	1049
Other non-metallic mineral products	**Manufacture of other non-metallic mineral products**	Manufacture of ceramic household and ornamental articles	0.048	2971	0.143
Other non-metallic mineral products	**Manufacture of other non-metallic mineral products**	Manufacture of ceramic sanitary fixtures	0.633	0.238	0.151
Other non-metallic mineral products	**Manufacture of other non-metallic mineral products**	Manufacture of ceramic insulators and insulating fittings	0.42	0.398	0.167
Other non-metallic mineral products	**Manufacture of other non-metallic mineral products**	Manufacture of other technical ceramic products	0.555	0.33	0.183
Other non-metallic mineral products	**Manufacture of other non-metallic mineral products**	Manufacture of other ceramic products	0.625	0.263	0.165
Other non-metallic mineral products	**Manufacture of other non-metallic mineral products**	Manufacture of lime and plaster	0.413	0.289	0.122
Other non-metallic mineral products	**Manufacture of other non-metallic mineral products**	Cutting, shaping and finishing of stone	0.049	20818	1021
Other non-metallic mineral products	**Manufacture of other non-metallic mineral products**	Production of abrasive products	0.398	0.033	0.013
Other non-metallic mineral products	**Manufacture of other non-metallic mineral products**	Manufacture of other non-metallic mineral products N.E.C.	0.522	0.111	0.058

Source: Compass Lexecon analysis based on EU's Carbon Leakage Regulation
Note: The sub-sectors considered here are based on the EU's NACE 2 codes. For further details, please refer to the appendix.
Note: Trade intensity is calculated as the sum of imports and exports divided by the sum of turnover and imports; the average of each sector was weighted by the value of each sub-sector application. Emission intensity is the sum of the direct and indirect emission intensity (DEI and IEI) in kg CO_2/€, with the DEI (IEI) being the ratio between direct (indirect) emissions and the GVA entire sector's direct (indirect) emissions, the average of each sector was weighted by the value of each sub-sector application. The carbon leakage indicator is the product of the trade intensity and the emission intensity.