Agora Industry

Agora Energiewende

STUDY

The business case for electrifying industrial heat

Evidence from selected EU Member States

Fraunhofer ISI

ECCO THE ITALIAN CLIMATE CHANGE THINK TANK

REFORM

Please cite as:

Agora Industry, Agora Energiewende, Fraunhofer ISI, ECCO Think Tank and Reform Institut (2026): The business case for electrifying industrial heat. Evidence from selected EU Member States. https://www.agora-industry.org/publications/the-business-case-for-electrifying-industrial-heat

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Acknowledgements
Christopher Berndt, Leandro Janke, Julia Metz, Lea Mohnen, Paul Munnich, Frank Peter, Nora Rauschke (Agora Industry), Alexandra Langenheld, Oliver Sartor (Formerly Agora Industry), Anna Kraus, Émeline Spire, (Agora Energiewende), Kaisa Amaral, Lena Tropschug (Agora Think Tanks), Chiara Di Mambro, Giulia Novati (ECCO Think Tank), Agnieszka Boratyńska, Aleksandr Śniegocki (Reform Institute)

Preface

Dear reader,

Reducing Europe's reliance on imported fossil fuels while safeguarding industrial competitiveness is an urgent EU priority. Exposure to volatile energy markets and geopolitical risks continues to burden the economy, with industry particularly affected due to its high demand for process heat. As heat accounts for over half of industrial energy use, shifting away from fossil fuels is a critical lever to strengthen energy security and resilience.

Electrification is increasingly recognised as a cost-effective solution. Mature technologies such as industrial heat pumps and electric boilers can already supply a large share of low- and medium-temperature heat, which together represent around half of industrial process heat demand.

Our analysis shows that, under the right market and policy conditions, electrification can outperform fossil-based and other low-carbon options. Realising this potential requires a coherent policy framework aligning electricity pricing, carbon pricing, grid regulation and industrial planning. This study assesses the techno-economic potential of electrifying industrial process heat in Europe, draws on country case studies and outlines policy recommendations to support a rapid, competitive and secure industrial transformation.

We wish you a pleasant reading!

Julia Metz
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Key findings at a glance

1 **Electrification is a strategic lever to safeguard Europe against fossil fuel price volatility and geopolitical risks.** The EU spends hundreds of billions annually on fossil fuel imports, with around 90 percent of oil and gas sourced externally. As process heat accounts for over half of the EU's industrial energy consumption, its electrification offers a major opportunity to cut emissions and strengthen economic resilience using largely mature and domestic technologies.

2 **Low- and medium-temperature processes – which account for half of industrial process heat demand – offer substantial and near-term electrification potential.** About 15 percent of process heat in Europe is low temperature (<80 degrees Celsius). These processes can already be electrified competitively compared to fossil gas-based applications under the current conditions thanks to the high efficiency of heat pumps.

3 **Germany, Italy and Poland show that electrifying low- and medium-temperature industrial heat can outperform fossil and low-carbon alternatives under the right conditions.** Over 2025–2050, costs could fall by about 20 percent if heat pumps are deployed where feasible and retail electricity prices stay below three times gas prices – compared with today's 3–5 range. Accelerated renewables deployment, a meaningful carbon price and lower electricity taxation are essential to creating these conditions.

4 **The forthcoming Electrification Action Plan should establish a coherent framework to scale electrification.** This should include short-term capital and operating support for heating applications above 80 degrees Celsius, grid fees that reward flexible loads to enable the use of electric boilers, and the integration of industrial demand into grid planning and adequacy assessments. National heat strategies should also provide long-term visibility, while supporting skills development and coordinated infrastructure planning.

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List of abbreviations

Term	Explanation
BAU	Business as usual
BEHG	*Brennstoffemissionshandelsgesetz* (German national carbon emission tax until 2027. From 2027: EU-ETS2)
BM	Biomass boiler
BNetzA	*Bundesnetzagentur* (German federal network agency)
CAPEX	Capital expenditure
CCfD	Carbon Contracts for Difference
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CHP	Combined heat and power
CID	Clean Industry Deal
COP	Coefficient of performance
EB	Electrode boiler
EIB	European Investment Bank
ETS	Emission Trading scheme
EU	European Union
FED	Final energy demand
FLH	Full load hours
GHG	Greenhouse gas
HP	Heat pump
HTHP	High-temperature heat pump
kWh	Kilowattt hour
LCOE	Levelised cost of electricity
LCOH	Levelised cost of heat
LTHP	Low-temperature heat pump
Mt	Megaton
MWh	Megawatt hour
NG	Natural gas
PPA	Power purchase agreement
TWh	Terawatt hour

1 Executive summary

Against a backdrop of intensifying geopolitical tensions and accelerating decarbonisation imperatives, electrification has emerged as a strategic pathway to enhance Europe's resilience and autonomy, and if pursued efficiently, its competitiveness. In 2023, the EU's energy import dependency was more than twice China's and more than three times higher than that of the US. This imbalance stems from the EU's continued reliance on imported oil and gas, which exceeds 90 percent of its overall demand. Such dependence exposes Europe to volatile prices – including on electricity markets for as long as fossil fuels continue to set prices at the margin – and supply disruptions. In addition, it results in a vast transfer of wealth to external suppliers. Despite the 2022 gas crisis having eased, the EU still spent 376 billion euros on imported fossil fuels in 2024.

Electrification, particularly if supported by increased renewable and low-carbon power generation, offers a means to reverse this predicament while reducing GHG emissions at the same time. By substituting imported fossil fuels with domestically produced electricity, Europe can retain value within its economy, enhance energy security and lay the foundations for a more sustainable energy system and competitive industrial fabric. Recent EU initiatives reflect this strategic reorientation. The RePowerEU plan sought to end dependence on Russian fossil fuels, while the Clean Industrial Deal framed electrification as central to Europe's competitiveness, setting an indicative target for Europe to use electricity to cover 32 percent of final energy consumption by 2030. Building on these, an Electrification Action Plan is expected in 2026.

Within this broader shift, industrial electrification stands out as both a challenge and an opportunity. Industry has been traditionally viewed as "hard to abate", yet this perception is changing. Process heat in particular – accounting for about half of European industry's final energy consumption and three quarters of its emissions – could be electrified for around 60 percent of its current fuel use using mature electrification technologies, rising to 90 percent with technologies expected by 2035.

In 2019, fossil fuels combustion supplied about three-quarters of industrial process heat in Europe, while electricity accounting for only 4 percent, largely concentrated in electric arc furnaces used for secondary steelmaking. However, low- and medium-temperature processes – which cover almost the entire heat range in the food and beverage, pulp and paper and textile industries, as well as a significant portion of process heat demand in the chemical industry – entail the greatest electrification potential since their respective heat demand aligns well with the operating range of mature electric heat appliances. Heat pumps, capable of delivering temperatures of up to 165 degrees Celsius today and potentially of up to 300 degrees Celsius by 2035, achieve high efficiencies by transforming rather than generating heat – making them suitable for e.g. drying, sterilising and pasteurising processes. Electric boilers complement them for higher-temperature or steam applications and can be easily integrated into existing systems.

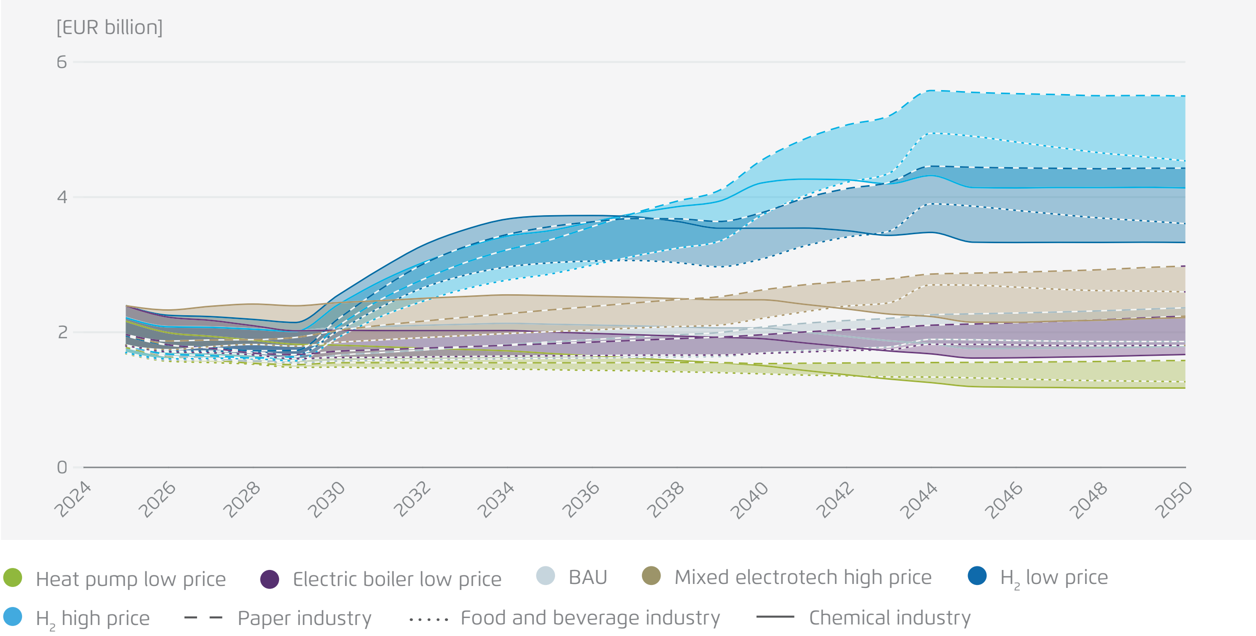
Against this backdrop, this study investigates the economic, environmental and energy security case for directly electrifying industrial process heat by comparison with fossil and low-carbon alternatives under varying national and sectoral conditions. It focuses on three EU Member States characterised by a strong industrial base and a significant reliance on fossil gas – Germany, Italy and Poland – to ascertain the impact of different power mixes and industrial specialisations. It uses scenario analyses to evaluate which conditions are required for electrification to strengthen Europe's industrial competitiveness while further reducing emissions and reliance on imported fuels.

The results of the case studies are broadly consistent across Germany, Italy and Poland: over the considered timeframe (2025–2050), direct electrification is the most effective and scalable way to cut emissions and reduce energy use for low- and medium-temperature process heat. Electrification is generally already cost competitive today for low-temperature heat (<80 degrees Celsius) due to the high efficiency of low-temperature heat pumps. Their high coefficient of performance allows them to remain economical even when electricity is four to five times more expensive than gas. However, to unlock the wider benefits of electrifying medium temperature heat and to ensure industry can decarbonise competitively, the electricity-to-gas price ratio needs to fall substantially – ideally to the 1.5–2.8 range. This can be achieved by lowering taxes and levies on electricity (e.g., by shifting the tax burden from electricity towards gas) in conjunction with effective and predictable carbon pricing.

In all countries, electrification-focused pathways deliver higher primary energy savings than the alternative pathways, delivering relevant energy security benefits. Hydrogen would only contribute to reducing emissions at a later date, thus resulting in higher cumulative emissions and entailing substantially higher costs than electrification pathways. The use of biomethane remains contingent on substantial subsidies that could well increase the overall costs of the transition compared to direct electrification. Though sustainable solid biomass appears to deliver cost gains, its use remains constrained by the uncertainty of its availability – an issue that also applies to the other low-carbon alternatives to direct electrification. In addition, given the limited availability of sustainable biomass, using it in sectors that are easy to electrify would be to the detriment of more valuable material uses - an externality that is not currently priced (Agora Energiewende et al., forthcoming).

The Germany case study shows that electrification can achieve sectoral carbon neutrality cost effectively by 2045, especially if heat pumps are deployed whenever permitted by the temperature range of the respective processes (Figure 1). Electrification becomes cost competitive when the electricity-to-gas price ratio, including carbon

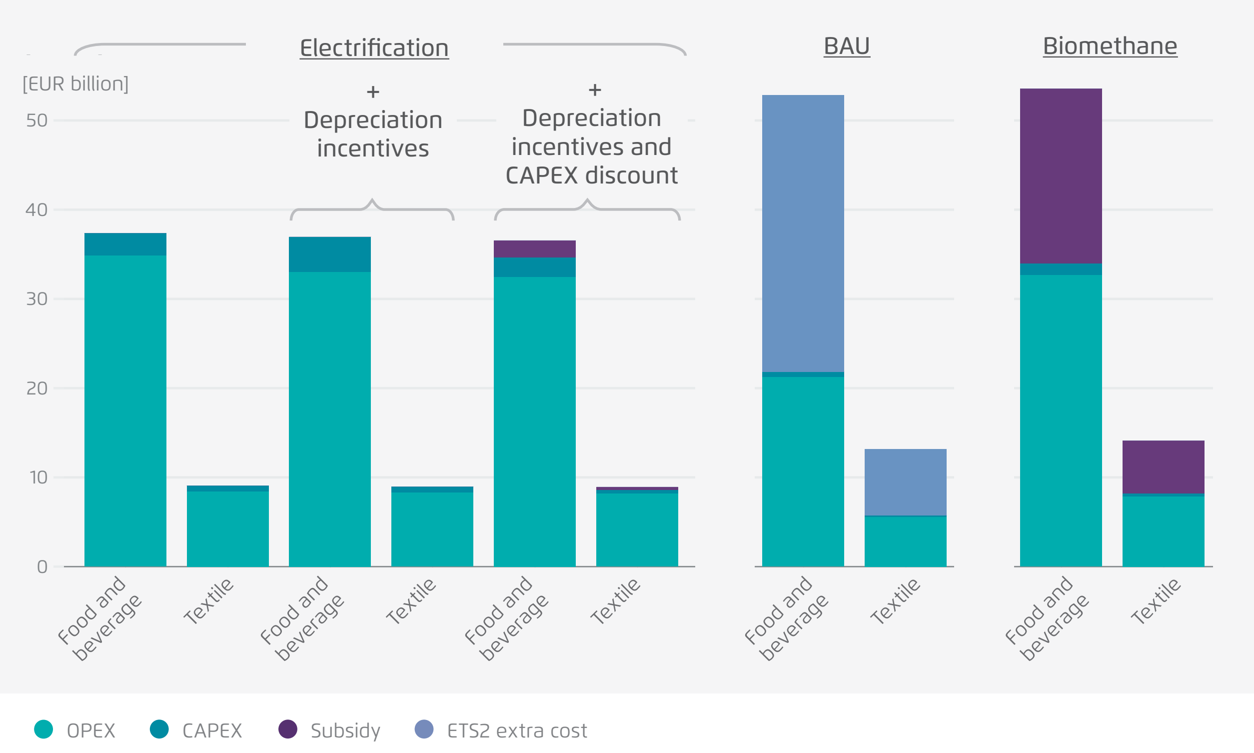
Cost per scenario in selected sectors, Germany → Fig. 1



Fraunhofer ISI (2025): Notes: For price assumptions for each scenario, see Tables 7-8; for technology assumptions for each scenario (Figure 35a/b) costs, decreases from the current 3–5 range for the sectors in question to the 1.5–2.8 range. Based on conservative assumptions about the wholesale electricity price, this could be achieved by reducing fees and levies on electricity – a process that is already underway – and by ambitious carbon pricing reaching 130 euros per tonne of carbon dioxide in 2030, and 180 euros per tonne of carbon dioxide in 2040. Hydrogen pathways remain significantly more expensive. Moreover, direct electrification reduces emissions earlier and to a greater extent and promises higher efficiency gains and fossil fuel savings than hydrogen-focused pathways.

Italy's analysis – performed for the food and beverage sector and textile industry – indicates that electrifying processes below 80 degrees Celsius, though already the lowest-cost option, represents only a limited proportion of industrial heat demand. Broader electrification becomes cost effective in the sectors in question between 2035 and 2040 as electricity prices decline compared to gas thanks to additional renewable and storage capacity, rising carbon costs under the ETS2 and decreasing technology costs. However, just a little policy support could make electrification cost competitive sooner. Policies ensuring faster asset depreciation and CAPEX support could bring the competitive deployment of electrification technologies forward to the mid-2030s, thereby achieving up to 85 percent electrification while saving 2.3 billion euros in cumulative costs over the period under consideration (Figure 2). Biomethane is uncompetitive without significant subsidisation and constrained by its limited availability. The case study warns of potential lock-in risks if industries continue investing in gas-based heat appliances because operating costs would soar by over 50 percent compared to electrification pathways if the electricity-gas cost gap were to decrease and carbon prices were to rise.

Cumulative costs by scenario and selected sectors in Italy, 2025–2050 → Fig. 2



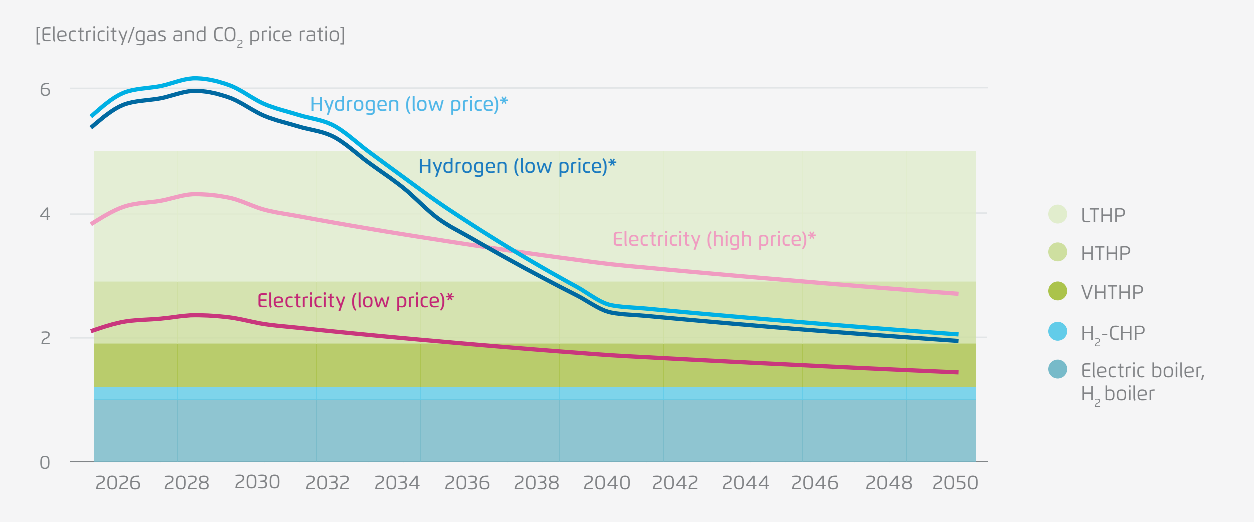
ECCO Think Tank (2025)

The Poland case study findings reflect the specificities of Poland's energy mix. While electrification is economically viable given a declining electricity-to-gas price ratio driven by carbon pricing and renewables expansion, the transition path varies by sector due to the differing temperature requirements of specific processes. The food and beverage sector could electrify fully at lower cost, whereas the paper industry will remain more competitive if it deploys an eclectic heat mix that still includes substantial use of biomass. Meanwhile, electrifying low-and medium-temperature processes in the chemical industry will only reach cost parity with the fossil alternative after 2040. Sustainable solid biomass remains cheaper in some contexts but is limited by supply constraints. Also, considering the maturity and scale of biomass-based technologies, fewer efficiency or cost improvements are expected compared with the relatively newer electrification technologies. Remarkably, despite the high emission-intensity of the Polish grid, electrification can achieve emissions reduction due to the high efficiency of heat pumps and the fact the electric boilers would initially replace highly emissive, ageing coal-fuelled heating appliances.

The national case studies in scope in this study reveal important similarities across Member States regarding the barriers to industrial electrification in low- and medium-temperature industrial processes. Given the availability and technological maturity of electrification solutions, these barriers are economic rather than technological in nature and can be addressed via appropriate policy design. Unfavourable electricity-to-gas price ratios limit the competitiveness of high-temperature heat pumps and electrode boilers (Figure 3). Additionally, existing network tariff structures discourage the flexible electricity use that electrode boilers require to operate economically. Grid capacity and connection costs constitute a further constraint given that most industrial sites were designed for fossil-based systems. From an organisational perspective, replacing fossil systems disrupts established production structures and requires skilled expertise. Furthermore, long equipment lifetimes can discourage early replacement. Policy uncertainty, limited knowledge transfer and misguided expectations of alternative fuel availability may also delay investment, underscoring the need for technological and policy clarity, economic support to fill short-term cost gaps and an infrastructural upgrade.

Energy carrier price comparison and efficiency potential of the technologies

→ Fig. 3



Fraunhofer ISI (2025); *gas price + ETS1; LTHP = Low-temperature heat pump, HTHP = High-temperature heat pump, VHTHP = Very-high-temperature heat pump, CHP = Combined heat and power; Note: Energy carrier and CO$_2$ price pathways reflect assumptions from Annex 1, Table 5

Accelerating industrial electrification requires economic, regulatory and governance levers to be mobilised in a coordinated manner. Economic levers should focus on ensuring that the electricity-to-gas price ratio declines predictably as a result of reduced taxes and levies on electricity, as well as predictable carbon pricing under ETS1 and ETS2. A carbon price of around 130 euros (EUR) per tonne of carbon dioxide (t CO_2) by 2030 and EUR 180/t CO_2 by 2040, combined with lower electricity taxation, would allow fossil gas to be phased out cost competitively in low- and medium-temperature industrial heat processes in the early 2040s.

However, some limited additional policy intervention will be required even if the business case is positive overall. As the EU is adopting an Electrification Action Plan, ten measures leveraging economic, regulatory, and governance levers have the potential to unleash industrial electrification by addressing economic, infrastructural and organisational barriers. These should include:

1. **Establish a predictable electricity-to-gas price pathway.** Electricity prices are decisive for electrification viability. Member States should rebalance taxes and levies to reduce the relative cost of electricity, using declining gas prices as an opportunity. Tax reform alone will not close current gaps, making carbon pricing and continued deployment of renewable power generation capacity central.

2. **Close short-term cost gaps with temporary support.** National schemes such as carbon contracts for difference help address operating cost gaps. To reduce market fragmentation and overcome limitations under state aid rules, EU-level instruments should complement them with temporary, conditional OPEX support. The recent Innovation Fund heat auction provides a blueprint including: competitive allocation, dedicated electrification baskets, SME access, incentives for flexibility, and a focus on temperature ranges above 80 °C.

3. **Streamline permitting for industrial electrification.** Create standardised fast-track permits for electrification projects by harmonising different local, regional, and national requirements. Establish one-stop-shop permitting portals, clear timelines, and "permit-by rule" pathways. Pre-approve common technologies, strengthen the staff and expertise of permitting authorities, and ensure coordination among utilities and regulators.

4. **Consider the introduction of gradually phased-in zero-carbon standards for new heat equipment below 500 °C.** To avoid fossil lock-in, zero-carbon standards could apply to new industrial heat installations in defined temperature ranges. Eligible technologies include heat pumps, electric boilers, waste heat recovery, solar thermal and geothermal systems. Biomass eligibility should reflect long-term resource constraints. The Industrial Emissions Directive could serve as the legal entry point.

5. **Support Member States in reforming electricity grid charges that enable flexibility.** Current network charge designs often penalise flexible electrification and storage solutions. Member States should introduce time-differentiated grid charges that reward system-serving flexibility and reduce incentives for constant consumption. Commission guidance issued in 2025 should be monitored and, if needed, reinforced through legislation.

6. **Set indicative deployment and fossil gas phase-out targets.** Clear demand signals are needed to unlock investment. The EU should set indicative electrification targets for 2030, 2035 and 2040 by heat class, alongside phase-out dates for fossil gas in low- and medium-temperature applications. An electricity share of 20–30 percent by 2030 and around 50 percent by 2040 is achievable under enabling conditions. Targets should be developed with industry to avoid demand-supply mismatches.

7. **Embed industrial electrification in the Energy Union framework.** The Energy Union governance revision should require Member States to develop dedicated clean industrial heat strategies. These strategies should feed into NECPs for 2030–2040 and transparently address electricity-to-gas price drivers and corrective measures. Electrification should be treated as a core energy security pillar due to its role in reducing import dependence.

8. **Integrate electrification into grid planning and connections.** Grid operators should explicitly account for industrial electrification in adequacy assessments and network planning. EU governance should define maximum connection timelines, support partial cost coverage under defined conditions and prioritise parallel processing of studies and permits. This would reduce delays and investment uncertainty.

9. **Mobilise public-private de-risking partnerships.** Public-private partnerships can reduce financing and operational risks for electrification projects. Electrification should be prioritised in tripartite contracts under the Affordable Energy Action Plan. Demand aggregation for SMEs could unlock cheaper financing, supported by national or EIB guarantees. Credit guarantees for PPAs can further reduce counterparty risk.

10. **Strengthen the EU electrotech manufacturing base.** An industrial electrification alliance should align deployment, manufacturing, skills and finance. By aggregating demand and improving project pipelines, it would provide manufacturers with visibility to invest in EU production capacity. The alliance should coordinate with EU industrial policy tools, including the Net-Zero Industry Act, InvestEU and the Competitiveness Fund. Support for non-yet mature electric heating technology should be mainstreamed in EU cleantech funding instruments including the Innovation Fund and Horizon Europe.

2 Background, purpose and subject of the study

2.1 Background

Against a backdrop of increasing geopolitical tensions, electrification is emerging as a favourable strategic choice for the European economy. In 2023, the EU's energy import dependency rate stood at 58 percent. This level of dependency is considerably higher than among Europe's competitors. In the US, net energy imports accounted for only around 17 percent of the total energy supply in 2024 – the country's lowest share in nearly four decades. China, despite being the world's largest energy consumer whose demand for oil and gas vastly exceeds domestic supply, recorded an overall energy import dependence of approximately 20 percent in 2022. The reason for this imbalance lies in Europe's heavy reliance on imported fossil fuels. In 2023, the EU imported 94.8 percent of its supply of crude oil and petroleum products, about 90 percent of its fossil gas supply and roughly 67 percent of its hard coal supply. Over the past decade, this dependence has increased. The consequences have relevant economic implications. In 2024, the EU spent 375.9 billion euros on imported fossil fuels. Even though this is far below the peak reached during the gas crisis of 2022, it nonetheless represents a massive transfer of wealth to external – and often politically adversarial – suppliers. Electrification offers an opportunity, especially as the European power mix becomes increasingly reliant on domestic renewable or low-carbon generation, to retain part of this value at home and to save resources that can be invested in the domestic power system and the economy in general.

A growing number of EU policy initiatives recognise this. The RePowerEU plan responded to Russia's aggression against Ukraine by devising a roadmap for phasing out EU dependence on Russian fossil fuel imports. The Clean Industrial Deal (CID) presented in 2025 places the emphasis on accelerating electrification as part of Europe's competitiveness, sovereignty and sustainability agenda, introducing an indicative, economy-wide target of 32 percent for the electricity share of final energy consumption. Based on this, the EU is expected to introduce an Electrification Action Plan in the first quarter of 2026,

Direct electrification is gaining traction for industry, which is generally considered to be harder to decarbonise than transport and buildings. This is largely the result of mounting exposure to the price volatility and, the geopolitical vagaries of imported fossil fuels and more realistic assumptions about the cost and availability of hydrogen or biofuels. Although direct electrification cannot support certain processes that require molecules as feedstock, it is attracting increasing policy attention when it comes to industrial applications involving process heat and other thermal uses. Heat generation accounts for roughly 50 percent of final energy consumption in European industry. Most of this comes courtesy of fossil fuels, namely fossil gas (35.3 percent), coal (18.7 percent), fuel oil (6.4 percent) and other fossils (14.2 percent). Due to this fossil fuel dominance, industrial process heat accounts for three quarters of industrial GHG emissions in the EU (Fraunhofer ISI 2024).

The potential for direct electrification in industrial process heat is substantial. According to the latest decarbonisation scenarios issued by the European Commission, electricity is set to do the heavy lifting. To reduce emissions by 90 percent compared to the 1990 level, the European Commission expects the share of electricity in industrial energy consumption to reach about 40 percent in 2030 under current policies and then to rise to around 48 percent in 2040 and 62 percent in 2050 (European Commission 2024). Importantly, these results show little variation across the different scenarios, indicating a high degree of confidence in the deployment potential of electrification technologies across a vast range of processes.

Many industrial processes could be electrified using available technologies such as industrial heat pumps, electric boilers, induction heating and electric arc furnaces. Overall, 60 percent of the industrial process heat that has not yet been electrified – predominantly in the low- and medium-temperature range for generating hot water and steam – could be electrified with existing mature technologies. The technologies expected to be available by 2035 could increase this share to 90 percent, especially in high temperature and capacity ranges (Fraunhofer ISI 2024). Nonetheless, progress on electrifying these applications has been slow. The share of industrial process heat that is currently electrified in the EU is estimated at about four percent (Fraunhofer ISI 2024).

Despite offering great technical potential and considerable benefits in terms of resilience and decarbonisation, the electrification of industrial process heat remains constrained by a combination of economic and organisational barriers. Technical limitations are no longer the main obstacles, especially for low- and medium-temperature heat where mature solutions are for the most part available. Particularly in the short term, economic barriers remain pronounced because industrial electricity prices are substantially higher than fossil alternatives – often more than three times the per-unit cost of fossil gas. Moreover, electrification requires upfront capital expenditure for new equipment – which is often manufactured based on *ad hoc* request and not yet produced at scale - and its implementation. The business case is often hampered by uncertainty over future energy and carbon prices, as well as by potential policy shifts. Organisational and infrastructural barriers also play a central role. Grid capacity and connection delays constrain electrification, while companies often lack the internal expertise necessary for the required transformation (Fraunhofer ISI 2024).

Coherent policy action is required to overcome these barriers, as failure to do so risks locking in another wave of investment in fossil fuel appliances, potentially entrenching external dependence and higher costs over the longer term.

2.2 Purpose of the study

The direct electrification of industrial process heat is a promising transformation path for the long-term competitiveness, resilience and decarbonisation of European industry. While its technical potential is widely acknowledged, its effective realisation depends on a broader set of conditions.

This study aims to clarify these conditions and provide an analytical basis for policy and industrial action at the EU level. It evaluates the economic feasibility, emission performance and energy security benefits of directly electrifying industrial process heat, taking into account the diversity of national power systems, national industrial specialisation and sectoral heat demand profiles across the EU. The study conducts a scenario analysis to identify when and where direct electrification becomes advantageous in practice. By integrating various energy and carbon price projections, process heat characteristics, technology maturities and prospects, the power grid's carbon intensity and the policy context into a dynamic perspective, the study assesses how direct electrification can help simultaneously to increase cost competitiveness, reduce emissions and lower fuel import dependence. In addition, it compares direct electrification pathways with alternative industrial decarbonisation options such as hydrogen, biomethane and solid biomass.

Ultimately, the purpose of this work is to support evidence-based decision-making as the EU is set to devise a strategy and adopt instruments to support industrial electrification. By clarifying the concrete circumstances under which electrification is beneficial, and by identifying barriers and enablers, the study provides insights for designing strategies to scale up industrial electrification in Europe.

2.3 Countries and sectors in focus

To translate these objectives into actionable insights, the study conducts scenario analyses of direct electrification in selected European industrial contexts. These analyses focus on low- and medium-temperature process heat – a heat range that offers the most immediate opportunities for electrification with commercially available technologies.

The study examines three EU Member States – Germany, Italy and Poland – chosen to represent large manufacturing bases with a high reliance on fossil energy, while also reflecting the diversity of Europe's energy and industrial landscape. These countries differ in terms of their power generation mix, industrial specialisation, energy cost structure and grid emissivity, allowing extensive insights to be obtained into how national conditions can shape the economic and environmental outcomes of direct electrification. Importantly, this is not a comparative study. Different partners and technical consultants carried out the scenario assessments in the individual Member States to reflect the analytical scope, assumptions and model design best suited to providing key insights into national dynamics. On this basis, the sectoral scope, scenario construction and methodology are individually reported in the country-specific sections.

The case study on Germany covers low- and medium-temperature heat in the food and beverage, pulp and paper and chemical industries, mostly assuming large, energy-intensive enterprises subject to ETS1 carbon pricing (with the exception of the food and beverage sector). Different carriers – fossil energy, electricity and hydrogen – are compared at different energy prices and with different types of electrification technology deployment with a view to reflecting electrification's cost sensitivity to energy price components and the varying efficiency of electric appliances. The case study on Italy identifies the most cost-efficient technological pathways on the basis of different energy market and policy dynamics. It contrasts the costs associated with the conditions required for large-scale electrification with those conducive to the large-scale deployment of biomethane and applies such scenario analyses to small and medium food and textile businesses subject to the ETS2 carbon price scheme. Finally, the case study on Poland conducts a scenario analysis of the food and beverage and pulp and paper sectors, as well as of a certain section of the chemical industry, namely the pharmaceutical industry. It compares a long-term 100 percent electrification pathway with a continuation of the largely fossil-based status quo and a more eclectic sectoral heat mix involving a large share of solid biomass (Table 1).

The study is structured as follows: Section 3 summarises the technologies covered by the study and explains why some were discarded from the analysis. Sections 4, 5 and 6 contain the scenario analyses of

Case study design

→ Table 1

Case study	Sectors	Assumed carbon pricing scheme	Main technological pathways under consideration	Main parameters for scenario construction
Germany	Food and beverage	ETS2	Fossil fuels Electrification Hydrogen	Levels of taxes and levies on energy Efficiencies of the technologies in scope
	Pulp and paper	ETS1		
	Chemical industry	ETS1		
Italy	Food and beverage	ETS2	Fossil fuels Electrification Biomethane	Energy market prices Policy intervention (incentives for depreciation, CAPEX support, subsidies)
	Textile	ETS2		
Poland	Food and beverage	ETS1, ETS2	Fossil fuels Mixed electrification – solid biomass Full electrification	Efficiencies of the technologies in scope
	Pulp and paper	ETS1		
	Chemical industry	ETS1		

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the individual Member States, each concluding with the main takeaways from the results. Section 7 looks at the scenario results in the context of the EU level, identifying key enablers and providing EU-level policy recommendations for unleashing electrification in Europe. Technical annexes contain the main assumptions and inputs relating to the national models.

3 Technological options for decarbonising low- and medium-temperature industrial process heat

Fossil fuels currently supply a large proportion of low- and medium-temperature industrial process heat. Boilers and combined heat and power (CHP) units are the main fossil fuel-based technologies in place. This section introduces the main technological options for decarbonising low- and medium-temperature process heat, while also explaining why certain decarbonisation technologies were excluded from the study's scope.

3.1 Electrification technologies

3.1.1 Industrial heat pumps

Heat pumps are unique among electrified heating technologies. Rather than converting electricity into heat, a heat pump moves heat from a "heat source") to a "heat sink", similar to a refrigerator moving heat from the cold interior to the warm exterior of the unit. A heat pump has a closed loop of piping filled with a refrigerant. Before passing through the heat source (typically the air or ground), the fluid passes through an expansion valve that lowers its pressure and causes it to evaporate and thus to cool. The fluid absorbs heat from the heat source and is then compressed, and as it condenses it heats up. The hot fluid then passes through a heat sink, such as water in the case of an industrial heat pump designed to produce steam. Heat passes from the refrigerant to the heat sink, and the refrigerant is pumped back to the expansion valve, beginning the cycle again.

Heat pumps can be used in a range of processes with relatively low temperatures and have very high efficiencies compared to conventional heating technologies. The system efficiency depends to a great extent on temperature lift and thus on careful integration into the industrial process. Physical laws and technically available refrigeration agents impose limitations on the achievable temperatures (and thus applications).

The typical maximum temperature output of commercialised heat pumps today is around 165 degrees Celsius (°C) (Arpagaus et al. 2018), though these high-temperature heat pumps have relatively small capacities (660 kilowatts, kW). Larger heat pumps (with a capacity of 20 megawatts, MW) are commercialised for temperatures of up to 100 °C (Madeddu et al. 2020). However, these estimated temperatures and the associated efficiencies depend primarily on the temperature lift. Higher temperatures can thus be reached with higher-temperature heat sources (e.g. waste heat from an industrial process). In combination with subsequent mechanical vapour recompression (MVR) or direct-electric temperature boosting, even higher temperatures can be reached – albeit at the cost of efficiency. In any case, the technology (compression, refrigerant, boost) for systems with temperatures up to 250 °C does exist. Research and development work is aiming to achieve higher temperatures still (Stathopoulos 2023), and it is likely to be possible to supply up to 300 °C heat by 2035 (Fraunhofer ISI 2024).

Since heat pumps move rather than generate heat, they are more efficient than other heating technologies. Heat pump efficiency is expressed as a coefficient of performance (COP), which is the ratio of output heat to input electricity. Heat pumps are most efficient when delivering relatively small temperature increases, and their efficiency drops as the temperature increase grows larger. This makes them attractive for the recovery of waste heat. For example, a heat pump that extracts heat at 60 °C and outputs steam at 180 °C has a COP of between 1.9 and 2.2 (Arpagaus et al. 2018). Increasing the output temperature reduces the COP, while raising the temperature from the heat source – e.g. by using more attractive waste heat steams – increases it.

While industrial scale heat pumps are already technically mature and available, their diffusion faces various challenges. Their installation requires an external heat source such as waste heat or ambient air and is thus more complex than fossil-fired boilers. Though the overall potential of these heat sources is expected to be more than sufficient (Agora Energiewende and Fraunhofer IEG 2023), site-specific conditions and the availability of heat sources are relevant factors to be considered. The fact that their investment costs are higher than for electric or gas-fired steam boilers (Agora Industry and Future Camp 2022) imposes a further limitation.

The most important applications for heat pumps are to be found in industries with demand for low- to medium-temperature heat and steam. These include food processing (for cooking, sterilising etc.), pulp and paper (pulping, bleaching), chemicals/plastics (driving chemical reactions, plastic moulding), textiles (drying, heat setting) and shaping metal parts for vehicles (Agora Industry and Future Camp 2022). In many applications, the required temperature level may be lowered by implementing appropriate efficiency and process optimisation measures at best-available-technology (BAT) level – thereby increasing the suitability and efficiency of heat pumps.

3.1.2 Electric boilers

Electric boilers are used in the same ways and applications as conventional boilers. Electric boilers are already established in industry. In industrial settings, electric boilers are gaining prominence due to their versatility, ease of installation and potential for high-temperature applications. Electric boilers (and heat pumps) can be used in steam-using applications in which CHP generation such as gas and steam turbines is relevant today.

Electric boilers come in two types: electrode and resistance boilers. In an electrode boiler, the current is introduced directly into the water via an anode and flows through the water to a cathode. In resistance boilers, an electric current heats a metal or ceramic heating element and the heating element transfers the heat to the water via conduction (Fleiter et al. 2023b). Electric boilers are available in a range of capacities, accommodating various industrial demands. They typically provide capacities ranging from small-scale applications at around 10 kW to large-scale systems exceeding 10 MW. Furthermore, these boilers can attain maximum temperatures above 500 °C, facilitating processes that necessitate elevated heat levels which heat pumps cannot provide. Pressure levels can vary based on specific requirements, typically reaching up to 20 bar, though higher pressures can be achieved (Fraunhofer ISI 2024).

The advantages that electric boilers offer over their conventional gas-fired counterparts are their higher efficiency levels, as they convert electrical energy into heat which is transferred directly into the medium without the energy losses associated with heat exchangers and flue gas. Additionally, electric boilers are inherently cleaner, emitting no greenhouse gases or pollutants during operation. Upfront costs for electric boiler installation and infrastructure combined can be higher than in traditional gas-fired systems. However, the most important barrier to wider use is the high price of electricity compared to fossil gas in most European countries.

3.2 Alternative fuels

Three main alternatives to electrification are considered in this study: hydrogen, biomethane and solid biomass. Depending on the specific sector and geographical context, these are the most discussed options for complementing or replacing direct electrification-based pathways in low- and medium-temperature heat industry.

3.2.1 Solid biomass boilers and CHP

Burning solid **biomass** rather than fossil gas in conventional processes requires only minor adjustments in terms of technical implementation and operation. Solid biomass would entail some advantages for plants which produce it as a by-product, e.g. in the form of black liquor, wood residues and cake sludge in the pulp and paper sector, as they could access fuel on site. Ideally, producing and using biomass could contribute to the urgently needed transformation of forestry and agriculture towards greater climate resilience and biodiversity. However, burning sustainable biomass also causes direct biogenic CO_2 emissions which, measured against the heat provided, can exceed those of the reference systems (for example, when fossil gas is used in a steam boiler). In addition, using biomass can pose a risk to food security and biodiversity without strict sustainability criteria. At larger scale, the mass use of biomass would lead to a loss of long-term carbon sinks, which wouldn't be the case if biomass were used as a construction material or as a source of carbon to produce chemical products.

3.2.2 Biomethane boilers and CHP

Biomethane is a purified version of biogas that is produced via the anaerobic digestion of organic matter in an oxygen-free environment, e.g. in biodigesters, wastewater treatment or landfill recovery facilities. Biomethane is produced by upgrading biogas or subjecting solid biomass to thermal gasification and methanation and is undistinguishable from fossil gas. As such, it offers the considerable advantage of requiring industrial users to make no modifications to process and equipment, be it traditional gas boilers or more efficient CHP units. In addition, certain sectors produce wet waste with a high organic content that is suitable for anaerobic digestion as a by-product and could thus benefit from on-site supply. Major question marks remain over availability and prices. The EU's RePowerEU plan fell short of its ambitious goals, demonstrating the scale of the challenge.

3.2.3 Hydrogen boilers and CHP

Hydrogen and its derivatives can deliver industrial process heat with relatively minor modifications to technical processes. It is particularly suitable for high-temperature heat and already envisaged as a feedstock (fertilisers) or reduction agent (steel) in industrial applications. However, green hydrogen is less efficient as it requires much more electricity than direct electrification to deliver the same unit of heat. Blue H_2 involves using gas, which has security implications and methane leakage issues, while also requiring carbon capture and storage (CCS). All in all, while a transition from fossil gas to hydrogen involves relatively limited changes in industrial processes, one must take into account the much higher level of system modification that such a transition implies. For these reasons, the use of hydrogen for decarbonising low- and medium-temperature process heat is regarded with criticism.

3.3 Technologies and carriers out of scope

Using **plastic waste** as an alternative fuel conflicts with the goals of an energy- and resource-efficient circular economy. In future, limited quantities of plastic waste will be needed primarily for higher-value material uses (Agora Industry 2022). Large amounts of CO_2 are released when typical plastic waste is incinerated, making this practice incompatible with climate neutrality.

Renewable heat sources include concentrated solar heating and geothermal heating. Concentrated solar heating (CSH) is suitable for areas with sufficient free space and without the infrastructure for direct electrification, on top of specific irradiation conditions. Geothermal heating involves some considerable risks (very high CAPEX), while more accessible geothermal energy is only suitable for certain geographic locations. All in all, these solutions require highly specific conditions and are more suitable for specific individual applications. As such, they are all outside the scope of this study.

Carbon capture and storage (CCS) technologies require no modifications to be made to existing fossil fuel-based process heat generation systems as they capture the carbon emissions of industrial plants. Though capable of serving all heat classes, they are best suited to large installations with centralised points of emissions. In addition, they require connection to carbon transport networks. Due to their limited viability for low- and medium-temperature heat, CCS technologies are outside the scope of our analysis.

4 Case study: Germany[1]

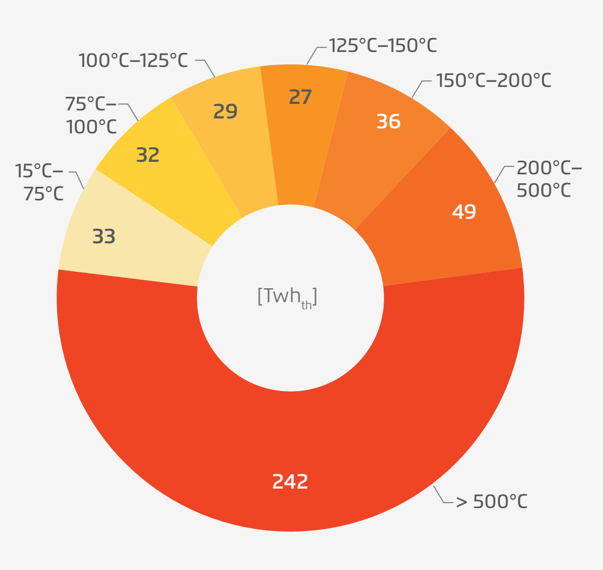
4.1 Sectoral scope

In Germany, low- to medium-temperature process heat accounts for 46 percent of industrial process heat (Figure 4). The industrial subsectors that primarily use low- and medium-temperature process heat are the food and beverage, pulp and paper and chemical industries (Figures 5–6).

4.1.1 Chemical industry

The **chemical industry** is a significant contributor to the German economy, creating approximately 200 billion euros in total value each year. Encompassing around 1,900 companies, this sector is responsible for about 30 percent of the country's industrial energy consumption, with an energy demand of 182 terawatt hours (TWh) and a feedstock demand of 236 TWh in 2022 (AG Energiebilanzen 2024). In terms of environmental impact, the chemical industry releases approximately 42 million tonnes of CO_2 annually (VCI 2024). The low- and medium-temperature heat demand of the German chemical sector amounts to about 39 TWh of heat (TWh_{th})(Fraunhofer ISI 2024).

Industrial process heat by temperature level in Germany, 2023 → Fig. 4



Fraunhofer ISI (2025) based on AG Energiebilanzen (2024)

Low- and medium-temperature processes in the chemical industry include:

- → **Heating of raw materials**: Many chemical reactions require raw materials to be preheated to facilitate the reaction. This often involves heating feedstocks to temperatures ranging from 100 to 200 °C.
- → **Distillation**: Distillation processes, used to separate components based on their boiling points, require significant amounts of heat. The reboilers in distillation columns typically operate at temperatures ranging from 150 to 300 °C, depending on the substances being separated.
- → **Chemical synthesis**: Various synthesis processes, for example to produce fertilisers, polymers and specialty chemicals, often operate at temperatures ranging from 150 to 400 °C. Heat is necessary to drive endothermic reactions and maintain optimal reaction conditions.
- → **Evaporation**: Evaporation is utilised in processes where solvents need to be removed and requires heat input to achieve temperatures of around 100 to 200 °C.

In the chemical industry, process heat demand at low and medium temperatures is mainly covered by steam, which is usually generated on site and then transported to the point of use. One particular feature of the chemical industry is its process interconnection, meaning there are many sources of waste heat that may be utilised. These vary between plants and must be analysed on a site-specific basis. For this reason, this report considers low- and medium-temperature steam that is supplied without utilising the sector's potential for generating high-temperature waste heat.

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[1] Based on Fraunhofer ISI (2025).

Various technologies are commonly used to generate steam in the chemical industry. Gas-fired boilers are widely used. Providing steam at temperatures of between 100 and 300 °C, they are favoured for their efficiency and cost effectiveness. Combined heat and power (CHP) systems, which generate both electricity and heat while utilising waste heat to produce steam, are also used. Chemical complexes are more likely than other sectors to use combined cycle gas turbine power plants (CCGT), which are significantly larger than, for example, the CHP systems used in the paper industry. CCGT plants supply a wide range of processes with electricity and steam. Fossil fuel-fired steam generators are widely used, particularly in older facilities. Various other fuels such as waste and smaller quantities of coal and biomass are also used. These technologies collectively highlight the sector's reliance on fossil fuels for steam generation.

Electrification is already being used in individual cases in the chemical industry, particularly in low- and medium-temperature applications in which electrode boilers and heat pumps are used for heating and low-pressure steam generation. However, there has been no widespread adoption of electrification for steam production as yet.

One major challenge is posed by the high-temperature requirements of many chemical processes, which often render current electric technologies economically unviable. Heat pumps struggle to reach the high temperatures needed in processes such as distillation and chemical synthesis. However, there are several ways of achieving high capacities and high temperatures, for example by adding systems for temperatures beyond ~240°C (32 bar) (MAN Energy Solutions 2025; Zander and Ingestrom 2025). Furthermore, the initial investment costs for installing electric heating systems can be significant, deterring some companies from making the transition. In addition, temperature differentiation between applications is often limited – with the highest required temperature of any given process or site defining the steam distribution conditions. Temperature-staged heat delivery improves the applicability of electrification options but requires structural modifications to several areas of existing systems.

Additional infrastructural limitations also play a role: upgrading electrical infrastructure to support increased demand can be costly and logistically challenging, particularly in older facilities. Furthermore, access to a sufficient electrical grid is crucial, as many facilities may need to extend their existing connected capacity to support large-scale electrification. Economic viability is another concern, as the price of electricity is often higher than that of fossil gas, making electric solutions less economically attractive for some companies despite offering potential long-term savings.

This report focuses particular attention on the supply of steam in the chemical industry and the total costs of ownership of process heat installations.

4.1.2 Pulp and paper industry

The **pulp and paper industry** operates approximately 90 plants in Germany (Die Papierindustrie 2024). Due to the economic slowdown, energy demand has been decreasing[2] in recent years, reaching 26 TWh in 2023 and generating 9.8 Mt CO_2 of emissions (Die Papierindustrie 2024). In the pulp and paper sector, steam is a critical input used in various stages of production, particularly for pulping, drying and finishing. For this reason, the analysis in this report for the pulp and paper sector concentrates on steam generation at different temperature levels.

→ **Pulping process**: During the pulping phase, steam is generated at temperatures ranging from 160 to 200 °C. This steam is essential for cooking wood chips in chemical pulping processes, such as kraft or sulfite methods, where it helps dissolve lignin and separate cellulose fibres.

→ **Drying process**: Once the pulp has been formed into sheets, steam is used to dry them, typically at temperatures of 120 to 180 °C. The steam is applied to heated cylinders, which help remove moisture

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[2] In particular, the scenarios we apply the techno-economic analyses to [8] are based on 2019 energy balance data and assumed greater growth of the sector's final energy demand by 2025. The insights and conclusions are not affected by this difference.

from the paper sheets, ensuring proper drying and improving the quality of the final product. The required temperature and energy depend on product type, throughput and the condition of the applied machinery.

→ **Finishing**: In the finishing stage, steam may also be utilised for processes such as calendering, which involves smoothing and compacting the paper. This requires steam at up to 200 °C to maintain the necessary moisture content and flexibility of the paper.

Electricity is used not only to generate steam but also to supply mechanical energy and, in some cases, additional heating. Many plants additionally use biogenic residues and rejects to generate energy (especially steam). Given the high level of demand for combined electricity and heat, CHP units represent an attractive techno-economic solution under current price environment. From a technical point of view, heat pumps are particularly appealing because they can for the most part achieve the required temperature level and offer significant potential for efficiency improvements. In cases where the temperature of the required steam exceeds the heat pump's capabilities[3], combining the pump with an electrode boiler is an option that may offer greater flexibility while at the same time lowering emissions. Other technology combinations (such as vapour compression) were not considered because they cannot be universally applied in all cases. Though hybrid systems that combine existing fossil-fuel solutions and electrode boilers are already being used in some cases, the widespread adoption of fully electrified solutions faces economic challenges.

4.1.3 Food and beverage industry

In Germany, the **food and beverage industry** comprises approximately 6,100 companies with an annual turnover of around 230 billion euros (Pascher et al. 2024). This sector is characterised by a significant level of process heat demand, estimated to be about 34 TWh_{th} per year (Fraunhofer ISI 2024). For the same year, emissions amounted to approximately 4.2 Mt CO_2 (Fraunhofer ISI 2024).

In the food and beverage sector, various processes require steam at different temperature levels and utilise a range of energy carriers for efficient production. Common processes and steam requirements include:

1. **Cooking and pasteurisation**: Steam at temperatures typically ranging between 120 and 140 °C is often required to cook raw materials (e.g. vegetables, meats) and pasteurise liquid products (e.g. juices, sauces). This temperature range ensures effective microbial reduction while preserving product quality.
2. **Sterilisation:** Canning and bottling operations often involve sterilisation to ensure food safety and extend shelf life. Generally, steam is required at temperatures of 120 to 130 °C, depending on the specific requirements of the food product and the type of packaging used.
3. **Drying:** Steam, combined with hot air, is often used to dry products such as fruits, vegetables and grains. The steam temperature can range from 80 to 120 °C, facilitating moisture removal while maintaining product integrity.
4. **Heating and cooking in food processing:** Various heating applications, such as blanching or cooking in batch or continuous systems, require steam in the 100 to 150 °C range, depending on the specific process and food type.
5. **Cleaning and sanitisation:** Cleaning processes for equipment and facilities often utilise steam as a sanitising agent, involving temperatures ranging from 100 to 150 °C,

Electrification faces several challenges in the food and beverage sector. While certain processes have already adopted electric technologies – such as

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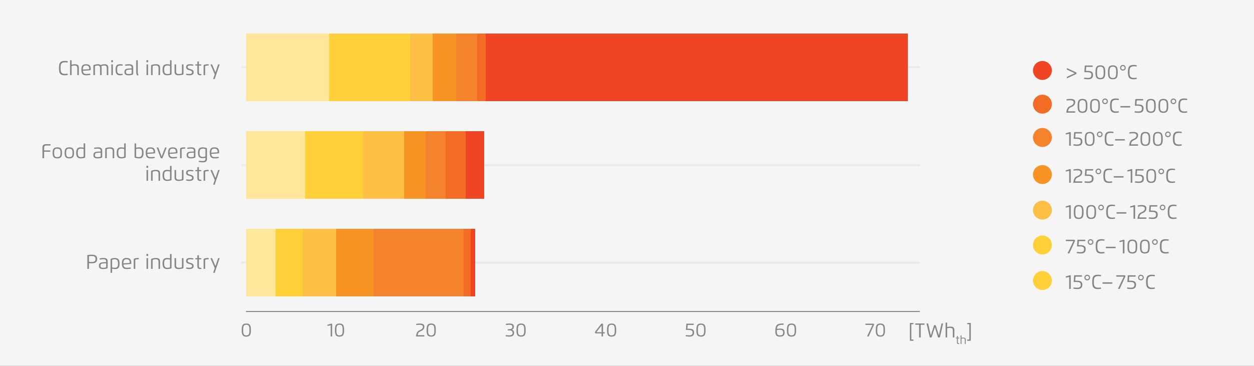
[3] The actual implementation of heat pump systems depends on on-site conditions – including the availability and usability of (internal) waste heat. Considerable uncertainties thus surround the achievable temperature levels. The 140–165°C range appears consensual when considering techno-economic limitations. The temperature level of heat demand depends on the paper machine and rotation speed, as longer machines and slower rotation can reduce the required temperature. However, these adjustments need to consider product quality and throughput.

Final energy demand for process heat in selected sectors in Germany by temperature level, 2023

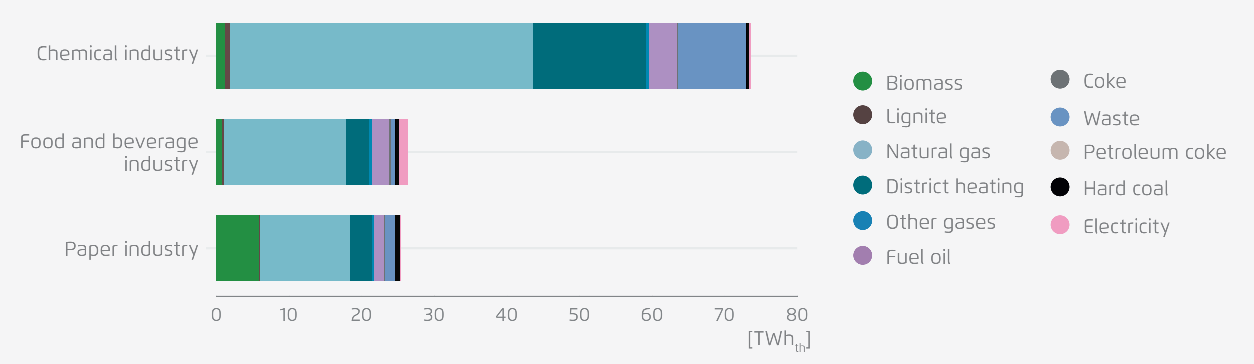
→ Fig. 5



Fraunhofer ISI (2025) based on AG Energiebilanzen (2024)

Final energy demand for process heat in selected sectors by energy carrier in Germany, 2023

→ Fig 6



Fraunhofer ISI (2025), FORECAST

electrode boilers for low- to medium-temperature steam production and specific applications in heating and pasteurisation – many areas rely on fossil gas-fuelled appliances such as boilers and CHP plants.

It is still uncommon for the steam generation process to be electrified these days, especially since heat pumps used to be capable of reaching temperatures of only up to 120 °C and electrode boilers offer a significantly smaller efficiency advantage that is insufficient to offset the difference between the price of fossil gas and electricity. High-temperature heat pumps are attractive but not yet in widespread use. As the costs of investing in this technology are significantly higher, this raises the question of whether it entails any decisive advantage in the form of improved efficiency. In addition to the investment costs, companies also face the expense of implementing measures to access ambient heat and to create the necessary electricity connection.

4.2 Scenarios

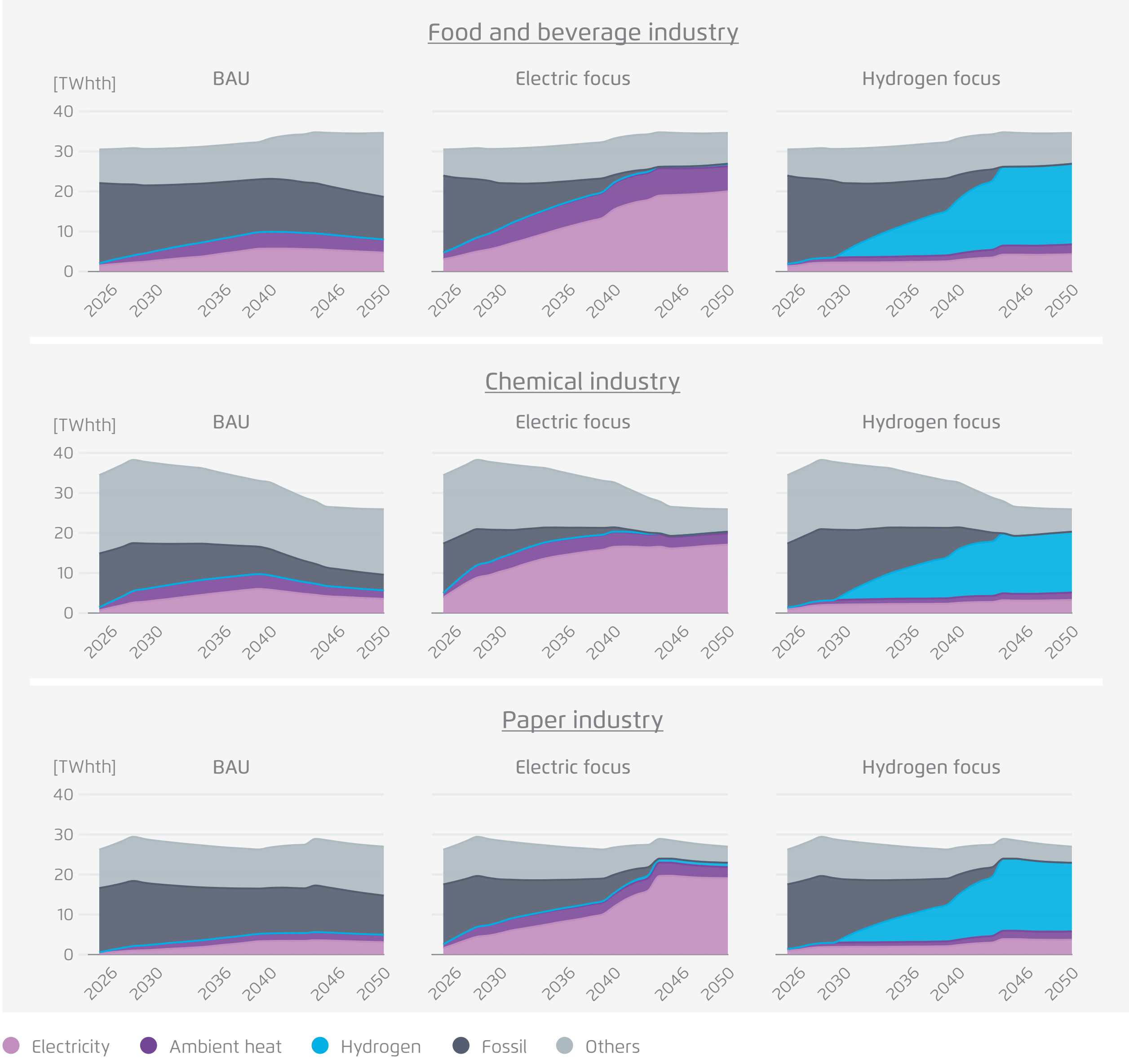
The scenario analysis identifies cost, CO_2 emission reduction and primary energy consumption trajectories across different technology combinations and energy price parameters. These are applied to the food and beverage, pulp and paper and chemical industries between 2025 and 2050. This section explains the scenario construction and methodology. Scenario assumptions are to be found in Annex 1.

4.2.1 Scenario construction

This analysis explores three main technological orientations based on fundamental technology choices: continued use of fossil energy, direct electrification or a high share of hydrogen. The electrification and hydrogen pathways are based on Fleiter et al. 2024. Under these scenarios, climate neutrality will be achieved by 2045 in line with Germany's Climate Change Act. In addition, a business-as-usual (BAU) scenario involving the continued use of fossil fuels under existing policies is based on the 2024

Low- and medium-temperature process heat demand by sector and energy carrier under the selected scenarios

→ Fig. 7



Fraunhofer ISI (2025), based on Fleiter et al. (2024) and Harthan et al. (2024); Note: the share of electrification and ambient heat does not reflect the allocation of these technologies requiring and not requiring ambient heat as an input – instead, they jointly indicate the contribution of electric appliances. A detailed visualisation of the specific allocation of this technologies, which is treated as an exogenous input in the modelling, is available in Annex 1, Figure 35a and 35b projections of the Federal Government (Harthan et al. 2024). Under the BAU scenario, decarbonisation is only partial, and climate neutrality is not achieved. Figure 7 shows the final energy demand per year by energy carrier in the different sectors in question for each scenario. In this context, the ambient heat category was included as an energy source for heat pumps. Other energy sources include biomass, waste and district heating[4]. Since these scenarios were each converted to the same total energy amount for the sake of comparability[5], they no longer represent the exact values from the data source; however, they do accurately reflect the composition of the respective energy carriers.

Within these three macro-orientations, the technology selected and the assumed energy carrier prices are differentiated, yielding scenarios that span a range of cost, energy use, CO_2 emission and efficiency trajectories. In total, six scenarios are selected, whose respective technology mixes are illustrated in Annex 1, Figure 36. These scenarios are based on two electricity and two hydrogen price pathways (Annex 1, Table 8). While any resulting divergence is the result of different levels of taxes and levies, these levels do not necessarily reflect current taxation levels and is employed solely to indicate a realistic range of the electricity-to-gas (plus CO_2) price ratio, thus reflecting the significant uncertainty surrounding future energy and carbon prices.

The **BAU scenario** serves as a reference scenario involving limited technological modification. In it, the electricity share of final energy consumption increases only modestly, and heat pumps account for a larger share than electrode boilers. Under this scenario, both electricity and hydrogen benefit from reduced taxes and levies.

Electrification scenarios

The electrification scenarios explore how different technology mixes and energy prices affect heating costs. The **heat pump low price scenario** is an electrification scenario characterised by high levels of efficiency and sees heat pumps deployed whenever technically possible – namely to cover all the demand for heat below 150 °C. Heat above this temperature is supplied by electric boilers and other efficient non-electric appliances. Under this scenario, taxes and levies on electricity and hydrogen are reduced.

In contrast, electrification in the **electric boiler low price scenario** is achieved solely with electric boilers. This scenario involves a generally less efficient technology mix, as molecule-based appliances only include boilers and no deployment of CHP units. Nevertheless, the limited efficiency of the technology mix is partly offset by the low retail electricity prices brought about by a reduction in taxes and levies.

The **mixed electrotech high price scenario** uses a more eclectic mix of electrification technologies in an attempt to achieve an efficiency middle ground between the heat pump and electric boiler scenarios. However, it tests a high degree of electrification in a price context unfavourable to electricity, where taxes and levies are fully applied.

Hydrogen scenarios

Among the hydrogen-focused scenarios, the **hydrogen low price scenario** involves a relatively energy-intensive mix in the sense that boilers are used for the most part as hydrogen appliances, no gas CHP systems are included and heat pumps are not used for electric heat. However, its low level of efficiency is offset by the reduced energy price assumptions for both electricity and hydrogen.

Finally, the **hydrogen high price scenario** focuses on a more efficient heat mix characterised by the use of hydrogen-fuelled CHP units and a combination of heat pumps and boilers as the electric appliances. CHP use is limited because hydrogen is more valuable

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[4] Biomass is used as an abstracted representative for "other heating options".

[5] The base scenarios answer different questions in their respective studies and thus include differences in overall industrial activity and economic development, e.g. relocation of processes and products. These differences have been compensated for by adjusting the final energy demand.

as a source of process heat than for electricity generation. However, since many firms plan to convert gas CHP systems to hydrogen, this option is included. Under this scenario, both hydrogen and electricity are subject to the full retail price including all taxes and levies.

4.2.2 Methodology

Costs are determined on the basis of the energy carrier mix (Figure 7), the technology mix (Annex 1, Figure 35a and 35b) and the price parameters of the respective scenarios (Annex 1, Table 8). Notably, the model does not perform cost optimisation – meaning that it assumes static behaviour without actors adjusting choices to minimise costs.

The levelised cost of heat (LCOH, expressed in EUR/MWh) is calculated annually for each technology mix from 2025 to 2050 (Annex 1, Section 8.2). For each year, the LCOH is aggregated across all the selected technologies according to their shares in the selected scenario and price structure. This aggregation yields the total costs of low and medium process heat for each sector under investigation.

CO_2 emissions are calculated by applying CO_2 intensities to the energy carriers. The indirect emissions incurred when electricity and hydrogen are used to generate heat are also taken into account.

A similar approach is adopted to estimate the primary energy demand in the different scenarios. Efficiency assumptions are applied to each technology (Annex 1, Table 7) to reflect their relative energy conversion efficiency. Notably, ambient and waste heat inputs are excluded from the primary energy balance. Primary energy consumption is then calculated by multiplying the energy input by the primary energy factor for each carrier (Annex 1, Table 9). The primary energy factor is nearly neutral for renewable energy, accounting for only minor grid losses. Hydrogen is assumed to use grid electricity.

The resulting trajectories for total costs, emissions and primary energy consumption are used to compare the different scenario combinations and evaluate the impact of different technology mixes and energy price developments.

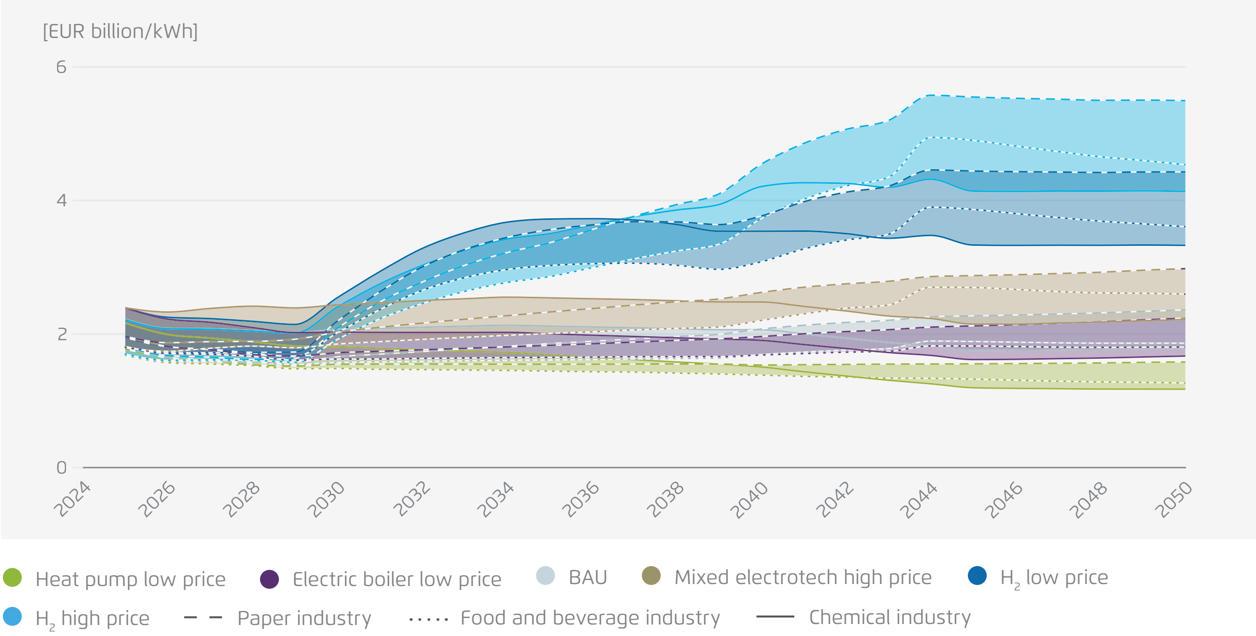
4.3 Results

4.3.1 Cost assessment

Until around 2030, costs remain on relatively similar trajectories as the scenarios diverge from the BAU scenario only gradually. Beyond 2030, however, the differences become more pronounced (Figure 8).

The electrification scenario with the largest share of heat pumps (heat pump low price) shows the lowest total cost. If heat pumps are deployed at scale and electricity prices are reduced through lower taxes and levies, annual savings of 294 million to 443 million euros compared to BAU are possible for the three sectors, achieving cost savings of 17–21 percent compared to BAU over the entire period (Figure 9). In contrast, the electrification scenario focusing on electrode boilers shows a more modest cost advantage (2–4 percent) over BAU in the food and beverage and chemical sectors, and a one percent disadvantage in the pulp and paper sector (Figure 9). Although the competitive use of electric boilers would require cost parity between electricity and gas – which is not achieved under the adopted price projection – the slight cost advantage of the electric boiler scenario vis-à-vis the BAU scenario is explained by slight efficiency and CAPEX gains, while the role of other technologies also has an impact on results. For example, the higher share of biomass and the higher temperature requirements in the case of the pulp and paper sector can help explain the slight increase in costs of the electric boiler scenario compared to BAU. The electrification scenario with full-price electricity (including full taxes and levies) shows cumulative costs that exceed the BAU level by 19–28 percent over the analysis period (Figure 9).

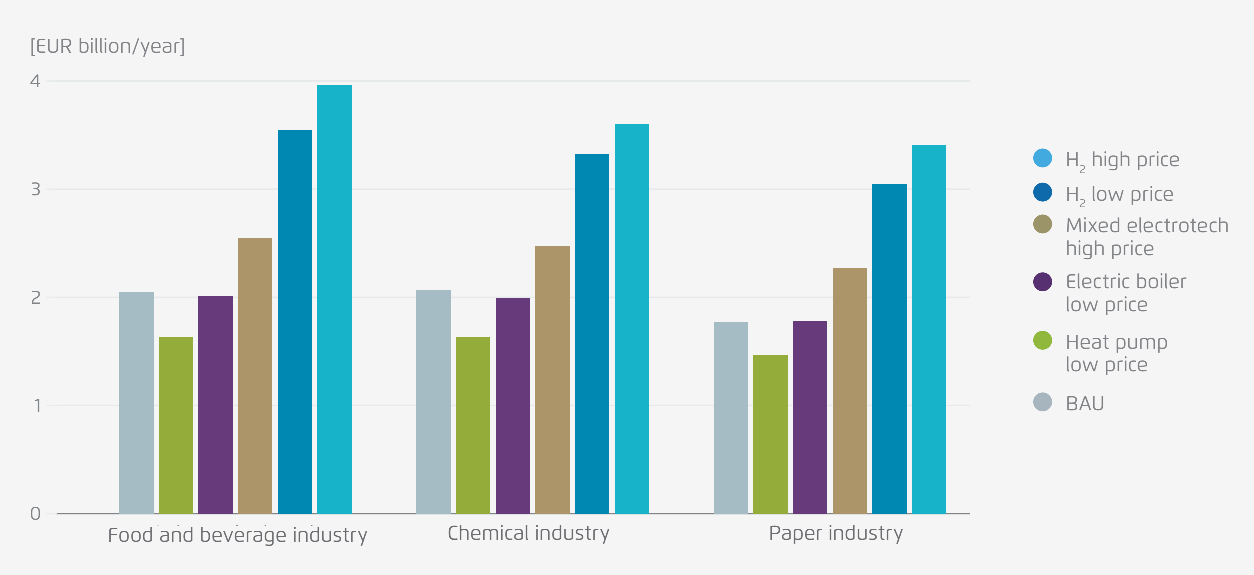
Cost per scenario in selected sectors, Germany → Fig. 8



Fraunhofer ISI (2025)

Hydrogen-focused scenarios, especially after 2030, stand out on account of their substantially higher costs – which are up to 1.5 or 2 times higher than in the electrification combinations (Figure 9). Increased imports would reduce the hydrogen costs over time, but even the least costly hydrogen scenario consistently exceeds the most expensive electricity scenario. These results make it clear that electrification based

Cumulative cost per scenario in selected sectors in Germany, 2025–2050 → Fig. 9



Fraunhofer ISI (2025)

on heat pumps is the most cost-effective strategy among those analysed, largely due to the significant efficiency advantage of heat pumps.

From an economic standpoint, heat pumps can already be viably deployed by 2025, especially for low-temperature process heat. Non-economic barriers – such as grid connection bottlenecks or the limited availability of ambient and waste heat – may thus be more decisive than costs in limiting adoption. For medium-temperature process heat, heat pumps become a favourable option from 2030 onwards, assuming technology improvements that allow higher output temperatures.

Energy costs – and electricity prices in particular – are the dominant component of overall process heat costs (Fraunhofer ISI 2025?). The results are thus sensitive to shifts in energy carrier prices – as indicated by the high and low electricity price scenarios. However, even considerable variations in both price paths point to consistent cost advantages for direct electrification in the industrial branches investigated.

To complement this dynamic view, a static comparison is included in Box 4.1. This provides a point-in-time analysis to support near-term investment decisions – particularly relevant for stakeholders seeking clarity on economic feasibility under current conditions.

Cost comparison of technologies in scope

The technologies described above were compared on the basis of the static levelised cost of heat (LCOH; see Annex 1, Section 8.2). For this analysis, three price levels (high, medium, low) were assumed for each of the energy carriers and the CO_2 price (Table 2) according to the price trends expected until 2050. In addition, assumptions were made regarding full load hours (6400 h/a), a factor for including electricity production from CHP plants (0.7) and the interest rate (five percent). These values were used to calculate the LCOH in EUR/kWh per technology. The results allow the different industrial heating technologies to be compared, helping to determine which technology is more economical at which energy carrier prices and which technology requires support to cover what cost gap.

Energy carriers and CO_2 prices for the LCOH static comparison → Table 2

	High energy price	Medium energy price	Low energy price	2024 parameter
Electricity	EUR 250/MWh	EUR 180/MWh	EUR 75/MWh	EUR 242.9/MWh
Hydrogen	EUR 300/MWh	EUR 200/MWh	EUR 90/MWh	
Gas	EUR 50/MWh	EUR 40/MWh	EUR 25/MWh	EUR 80.6/MWh
CO_2	EUR 210/t	EUR 145/t	EUR 80/t	
Electricity-to-gas (+CO_2) price ratio	≈2.71	≈2.60	≈1.82	≈3.01

Fraunhofer ISI; 2024 parameters: Eurostat 2026 (non-household consumption bands: electricity: IE (20 000 – 70 000 MWh); gas: I4 (100 000 – 999 999 TJ)).

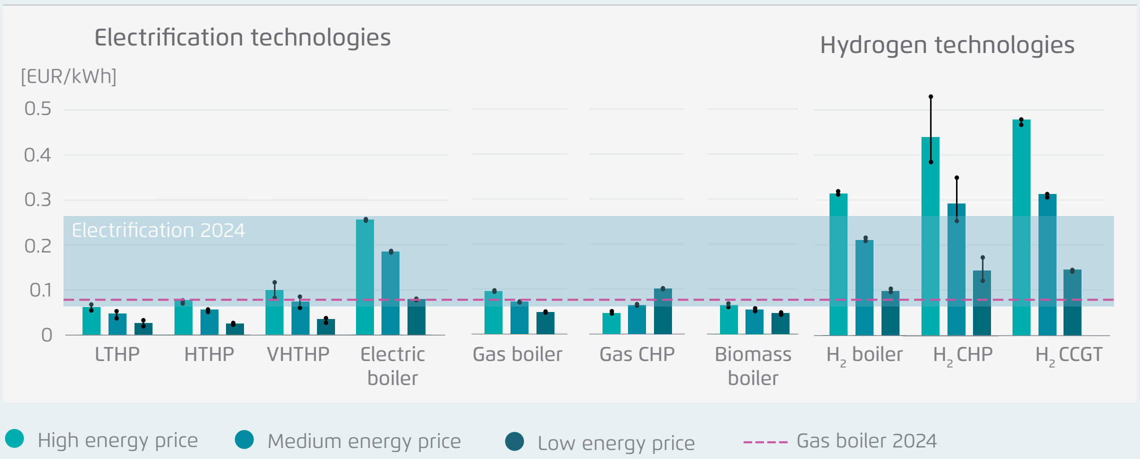
The technology comparison shows that electrification is competitive if heat pumps are used. Cost savings are particularly pronounced in the case of low-temperature heat pumps. However, heat pumps are unable to cover the entire medium-heat range that can be achieved by gas-fired boilers – and cannot therefore replace them fully in all applications. Though electrode boilers can cover the entire medium-temperature range, they are more expensive to operate because they are highly sensitive to electricity costs. While flexible operation can improve their economic viability, using them at high full load hour levels is not competitive because average electricity costs are higher than those of gas. When generating heat from gas, the CO_2 price is the dominant cost driver (accounting for 33 percent of the LCOH at low, 42 percent at medium and 48 percent at high energy prices). This impact is evident with CHP plants, where rising CO_2 costs combined with declining electricity prices make this technology increasingly uneconomical. The biomass boiler shows a consistently lower LCOH than the gas boiler*.

In all three cases, the heat generated by hydrogen technologies is more expensive than the alternatives, due to the high price of hydrogen and the high CAPEX assumed in the current literature. The use of CHP applications should be examined on a case-by-case basis. As hydrogen is more expensive than electricity, a hydrogen CHP system does not offer exactly the same benefit as a gas CHP system. Because of the uncertain outlook for hydrogen costs, cost reductions are possible. However, even in the best-case scenario, their costs still exceed the upper end of the range achieved by other technologies.

In summary, heat pumps capable of reaching temperatures of up to 165 °C can always compete with gas boilers in the low price scenarios, which assume an electricity-to-gas + CO_2 price of below 2. However, even at an electricity-to-gas + CO_2 price ratio of almost 3 (e.g. under the high price assumption in Table 2), heat pumps offer a relevant cost advantage at temperatures up to 100 °C. Under these assumptions, hydrogen technologies for generating low- and medium-temperature process heat show no economic attractiveness (Figure 10).

Levelised cost of heat of selected industrial heating technologies

→ Fig. 10



Fraunhofer ISI (2025); LTHP = Low-temperature heat pump, HTHP = High-temperature heat pump, VHTHP = Very-high-temperature heat pump, CHP = Combined heat and power, CCGT = Combined cycle gas turbine, LCOH = Levelised cost of heat; Note: for price assumptions, see Table 2, Comparison of LCOH without temporal classification of values.

* The costs assumed here for biomass are based on the assumption that it will be priced at the same level as natural gas but will not require emission certificates. Some companies will be able to obtain lower prices due to varying regional availability. However, the comprehensive use of biomass throughout Germany is subject to serious availability constraints. Furthermore, feedstock applications are likely to be prioritised over energy use (Banse et al. 2023)

4.3.2 Emission assessment

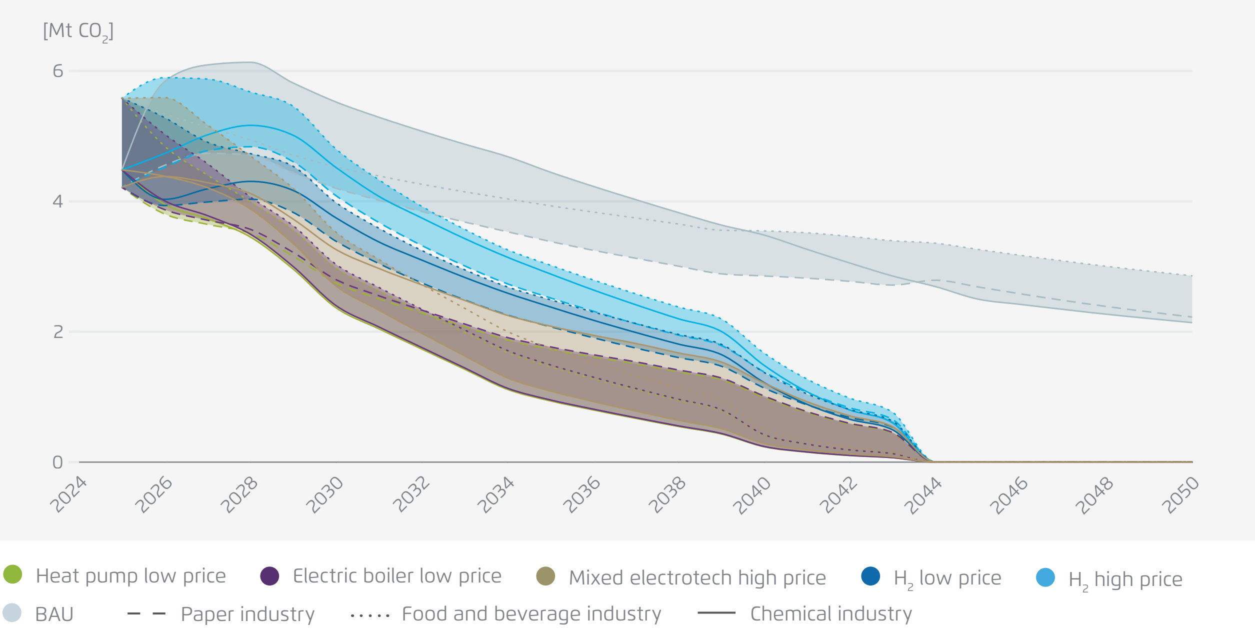
At the beginning of the period in question, the emissions associated with the electrification pathways largely reflect the indirect emissions incurred by the electricity grid. However, these emissions decrease significantly after 2030 (Figure 11), thus ensuring cumulative emission savings compared to the BAU scenario (Figure 12).

The electrification scenarios achieve the highest cumulative emission savings (Figures 11–12). By subsector, the chemical industry yields the highest savings (between 45 and 75 Mt CO_2), followed by the food and beverage sector (between 35 and 64 Mt CO_2) and the paper industry (between 35 and 52 Mt CO_2.). Though they also achieve climate neutrality, the hydrogen-based scenarios show lower emission reductions. The higher emissions incurred by hydrogen are due to the additional electricity consumed for domestic generation and the associated higher indirect emissions, as well as to the continued reliance on fossil gas in the early years when hydrogen availability is still limited. Over time, more hydrogen will be imported, bringing emissions closer to those of the electricity scenarios.

If CO_2 avoidance costs are considered, the higher costs associated with hydrogen-based scenarios become even clearer (Figure 13). In the hydrogen-based scenarios, CO_2 avoidance costs compared to the BAU scenario range from EUR 417 to EUR 1,140/t CO_2, while the range is close to zero in most electrification scenarios, and even negative at the highest share of heat pump deployment (EUR -110 to -170/t CO_2).

One point of concern with electrification technologies pertains to indirect emissions from the power sector. Figure 14 compares the indirect emissions from the electric technologies explored by this study with the direct emissions incurred by burning fossil gas in gas boilers. Heat pumps, with an assumed average coefficient of performance (COP) of 3, reduce emissions even with the electricity generation mix that was in place in Germany in 2024 (363 grams of CO_2/kWh (Umweltbundesamt 2025)). In 2025, the

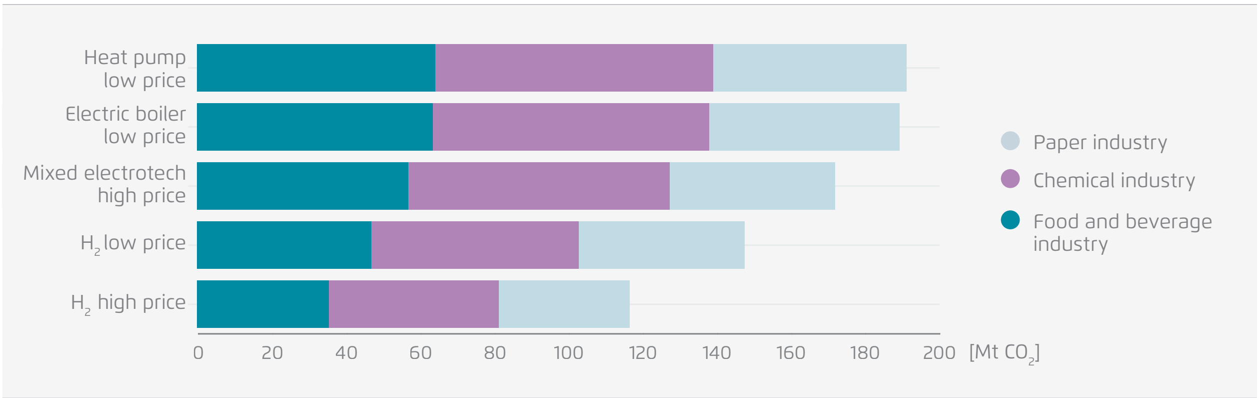
CO_2 emissions per scenario in the selected sectors, Germany → Fig. 11



Fraunhofer ISI (2025)

Cumulative CO_2 emission savings compared to the BAU scenario by decarbonisation scenario and selected sectors in Germany, 2025–2050

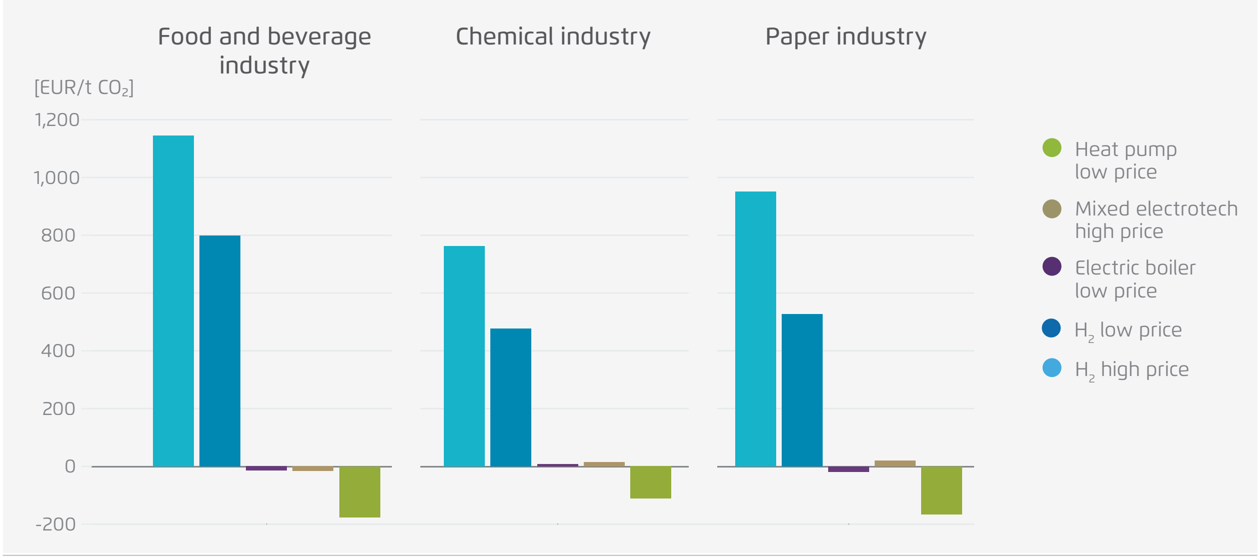
→ Fig. 12



Fraunhofer ISI (2025)

CO_2 avoidance costs compared to BAU by decarbonisation scenario and selected sectors in Germany, 2025–2050

→ Fig. 13



Fraunhofer ISI (2025)

indirect emissions of electrode boilers still exceed the direct emissions of gas boilers per unit of heat generated. From around 2030, as the power system is decarbonised, electrode boilers will also help reduce emissions. Even before then, it will be possible to lower emissions if electrode boilers are operated flexibly in hybrid systems, taking advantage of periods with a high share of renewables in the electricity mix – which will also lead to cost savings (Box 4.2).

In both cases, the cumulated lifetime emissions of electrode boilers are expected to be lower than those of fossil gas-fired boilers.[6]

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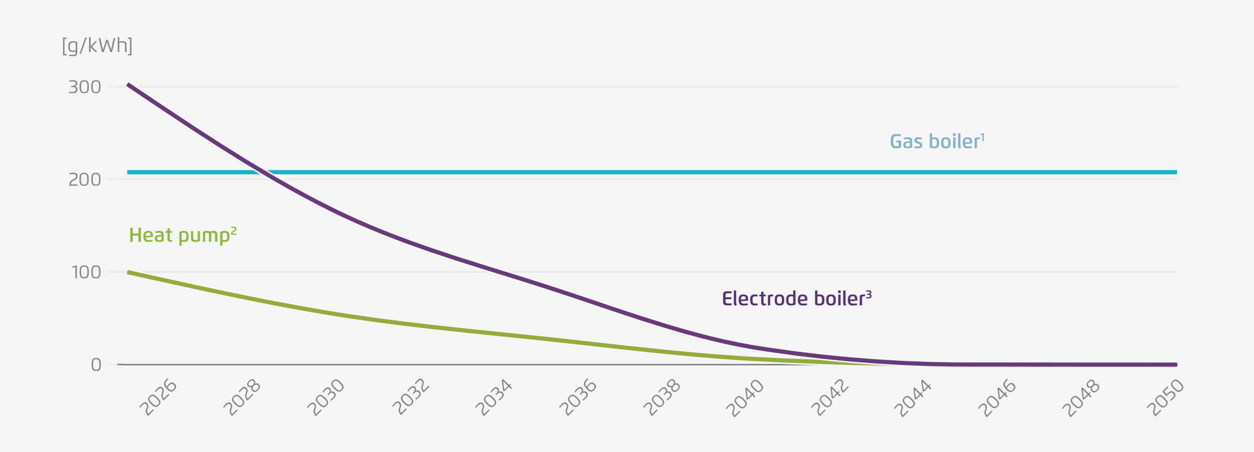
[6] If the areas below the emission values in Figure 17 are compared, the area covered by the electrode boiler or heat pump is significantly smaller than that covered by the gas boiler. If a service life of 20 years is assumed, this also applies to the period from 2025 to 2045. It can therefore be concluded that, even today, an investment will contribute to reducing CO_2 emissions over the entire lifetime.

CO$_2$ emissions of electric heating technologies and natural gas boilers in Germany → Fig. 14



Fraunhofer ISI (2025); ¹η = 0.97, ²coefficient of performance = 3, ³η = 0.99

4.3.3 Primary energy consumption assessment

Analysing the primary energy consumption shows similar results. Electrification-focused combinations with a high share of heat pumps (Heat pump low price and Mixed electrotech high price) achieve the lowest primary energy consumption, reducing the primary energy demand of the system to approximately 50 percent of the final energy demand (FED) (Figure 15).[7] The BAU scenario exhibits a higher primary energy demand, albeit declining from 127 to 108 percent of the FED. Electrification using only electrode boilers does not lead to substantial primary energy savings. The electrification scenario without heat pumps (electric boiler low price) ends up about eight percentage points above the BAU. Scenarios involving a high use of hydrogen show higher primary energy consumption (between 40 and 50 percent above FED) due to the conversion losses in the electrolysis phase. As a result, they are less efficient than the BAU and electrification scenarios.

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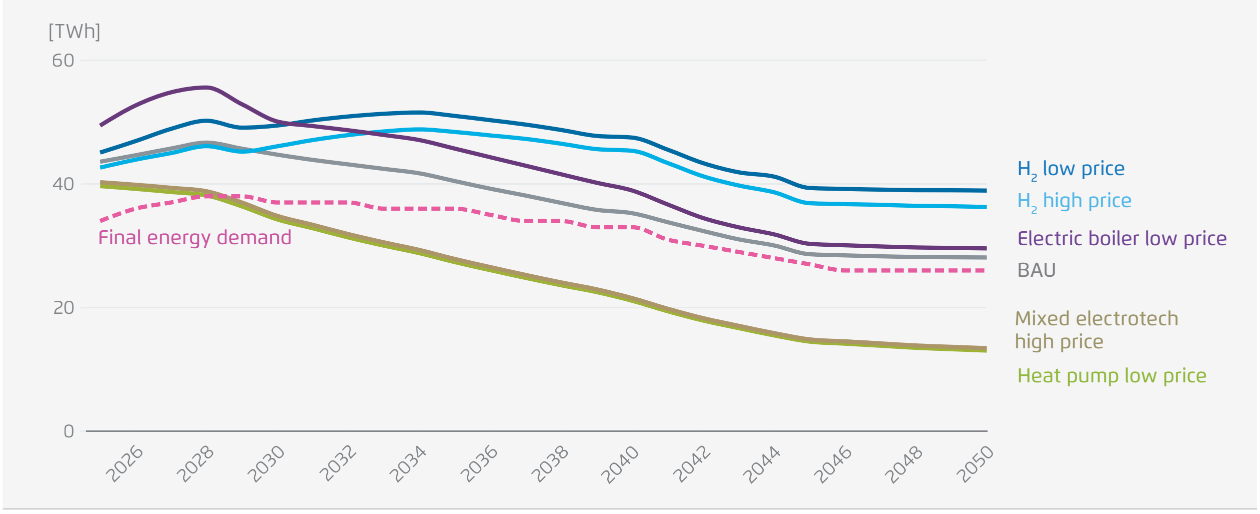
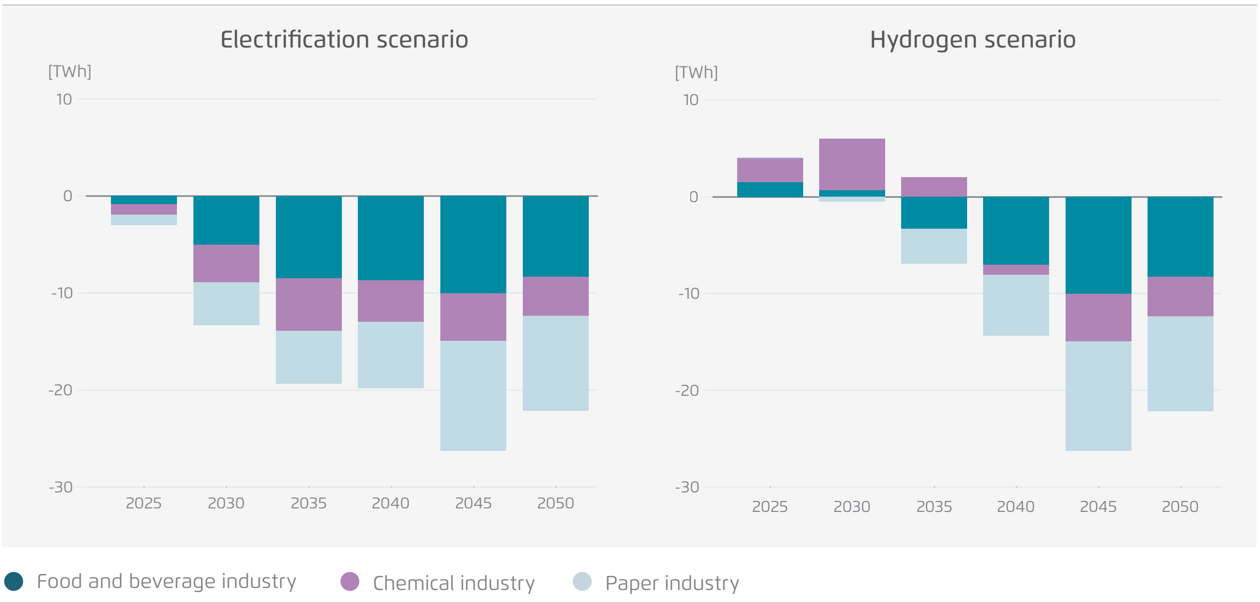
[7] Ambient and waste heat are not included in the analysis of primary energy consumption.

Primary energy consumption in selected sectors' low-and medium-temperature processes in different scenarios in Germany → Fig. 15



Fraunhofer ISI (2025)

Avoided fossil energy demand in the electrification and hydrogen pathways in selected industrial sectors in Germany → Fig. 16



Fraunhofer ISI (2025)

Electrification and hydrogen scenarios both reduce fossil energy use (Figure 16) compared to the BAU scenario. Electrification scenarios enable higher fossil energy savings (averaging 64 percent) than hydrogen (averaging 37 percent) between 2025 and 2040. The hydrogen scenarios are close to or below the BAU scenario in the early years, since low hydrogen availability and high prices imply a continued use of fossil-fired burners. Whereas both scenarios achieve the climate neutrality target in 2045, hydrogen-based pathways imply higher cumulative fossil fuel use, underscoring the superior energy security benefits of direct electrification-based pathways.

Hybridised electrification

The scenarios in this study consider energy costs based on an annual basis, which limits their ability to fully capture the potential cost and emission reduction benefits of operating electric appliances exclusively during periods of low electricity prices. To explore this aspect further, a comparison between a gas boiler and an electrode boiler is included in this box. Both technologies are assessed using medium energy price assumptions (see Table 1). Based on the German electricity price curve for 2024 (Bundesnetzagentur 2025), the analysis determines the number of hours during which the electrode boiler could operate more cost effectively than the gas boiler.

This analysis considers three scenarios based on different price conditions. Scenario 1 (S1) reflects current (2025) energy and carbon prices and current price fluctuations. Scenario 2 (S2) applies projected parameters for 2040 and current price fluctuations. Scenario 3 (S3) applies projected parameters for 2040 but assumes increased electricity price fluctuations (Table 3). Current price fluctuations are based on day-ahead prices from 2024. Increased fluctuations are the result of manually increasing the number of hours with very high and very low prices, reflecting a possible future in which more renewables are deployed but storage capacity is limited. The parameters are applied to a firm that pays EUR 12,864/MWh in taxes, levies and grid fees, a profile that is representative of large paper mills and the chemical industries, for example. This is a simplification, as the grid fee and levies also depend on the amount of electricity consumed – a factor not accounted for here. In addition, the Federal Network Agency (BNetzA) is currently working on a reform of grid charges aimed at simplifying the flexible procurement of electricity. Figures 17–19 show the results across the three scenarios. The diagrams illustrate the cost difference based on the hourly electricity price curve. An upward trend in the line means that the electric boiler is cheaper to operate than a gas boiler during that hour.

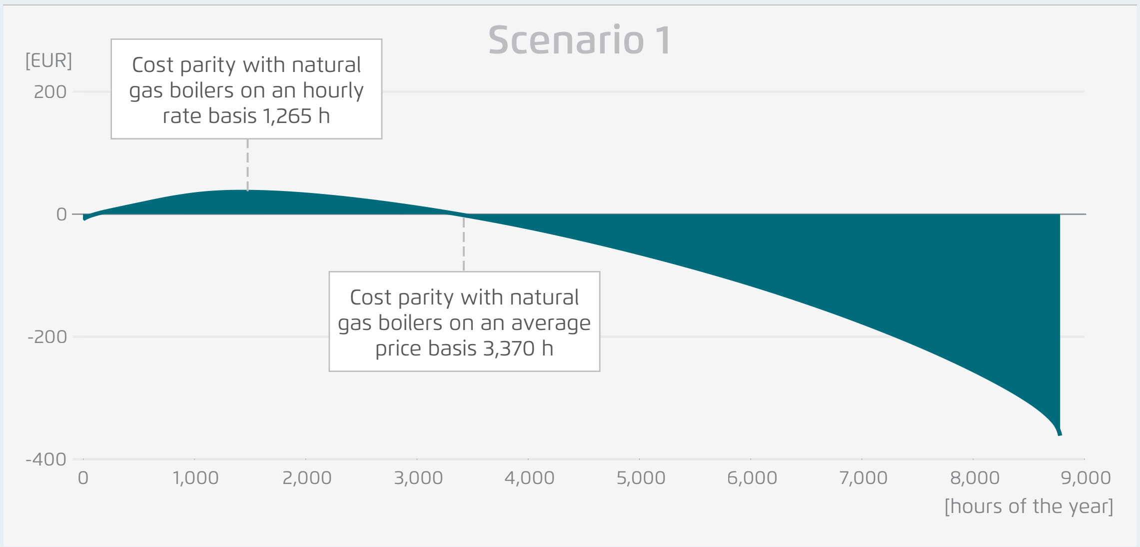
Parameter overview for the analysis of hybridised electrification → Table 3

Parameter overview	S1 (2025)	S2/S3 (2040)
Fossil Gas Price [EUR/MWh]	30	35
CO_2 Price [EUR/t]	85	200
Grid fees and reduced levies [EUR/MWh]	12.864	12.864

Fraunhofer ISI (2025)

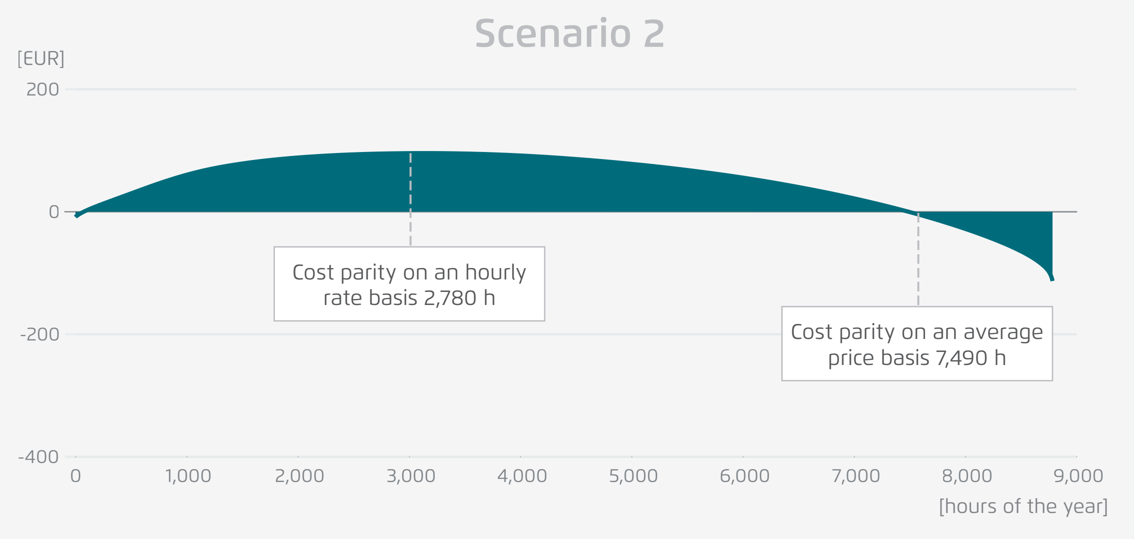
Even under current conditions, an electrode boiler can be operated at lower cost than a gas boiler for about 1,265 hours per year. If the price is averaged – meaning that the electrode boiler is operated during all the hours when its heat generation costs are below the annual average costs of gas-based heat – this value increases to 3,370 hours, equivalent to 38 percent of the year. Looking ahead to 2040, the cost advantage grows. In the less volatile electricity price scenario, the electrode boiler can operate below the price of gas-based heat for 2,780 hours or 32 percent of the year. In the more volatile scenario, this number increases to 3,500 hours or 40 percent. The hours in which the cost advantage is average

Cost comparison between electrode boilers and gas boilers → Fig. 17



Fraunhofer ISI (2025)

Cost comparison between electrode boilers and gas boilers → Fig. 18

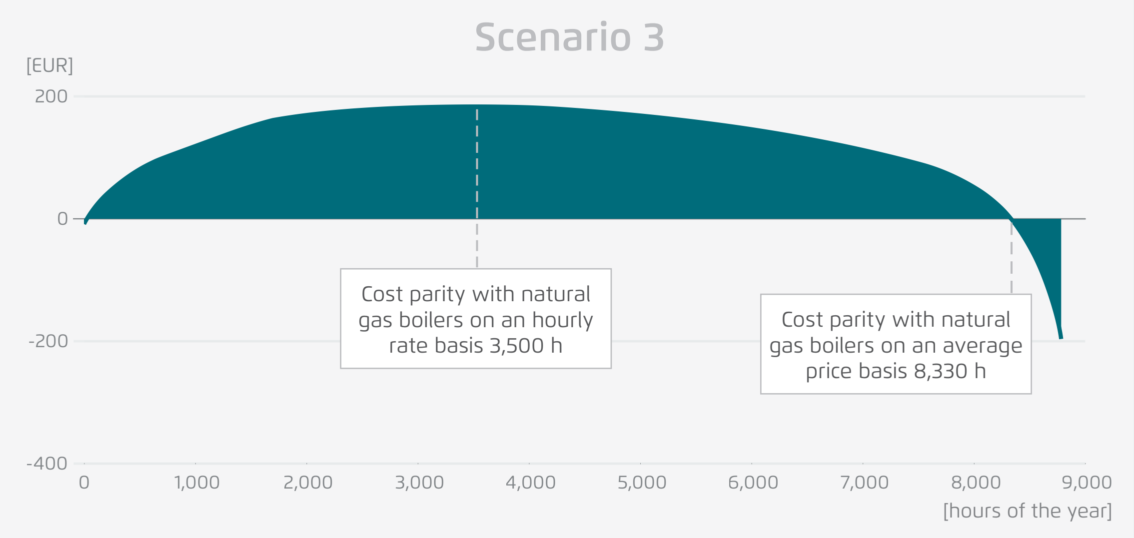


Cost parity on an hourly rate basis 2,780 h

Cost parity on an average price basis 7,490 h

Fraunhofer ISI (2025)

Cost comparison between electrode boilers and gas boilers → Fig. 19



Cost parity with natural gas boilers on an hourly rate basis 3,500 h

Cost parity with natural gas boilers on an average price basis 8,330 h

Fraunhofer ISI (2025)

total 7,490 and 8,330 respectively. The electrode boiler can therefore be used as the primary source, with the gas boiler acting as a backup during those hours when electricity is expensive. The outlook until 2040 is uncertain, as volatile price dynamics may lead to competition between storage operators during negative or near-zero price hours. However, both future scenarios highlight the advantage of hybrid electrification, which is why increasing volatility should not be a significant barrier to industrial electrification.

4.4 Main takeaways

Within the framework of this analysis, both direct and indirect electrification achieve climate neutrality for those branches of industry investigated. However, their performance in terms of costs, emission reduction and energy savings differs. Direct electrification results in lower costs and faster emission reduction. Three key findings are outlined below.

First, direct electrification can be used to achieve carbon neutrality in the sectors in question over the analysed timeframe at lower cost than in the business-as-usual scenario. This requires heat pumps to be used wherever technically feasible. Such opportunities are amply available in the paper, food and beverage and chemical industries, where 56 percent, 76 percent and 32 percent of final energy demand is below 150 °C – i.e. in a heat range that can be supplied by heat pumps. The electricity-to-gas price ratio – which is a function of energy prices, carbon prices and taxes, levies and charges – is a key determinant of the economic attractiveness of electrification. Policy measures that reduce the relative price of electricity compared to fossil fuels – for example by reducing taxes and levies on electricity and gradually increasing CO_2 prices – are therefore relevant levers for electrification.

Though heat pumps that reach temperatures of up to 80 °C are already economically viable, they cover only a limited segment of the heat demand of the sectors in question. It is feasible to reach temperatures of up to 100 °C at an electricity-to-gas price ratio (including CO_2-prices) of almost 3. Using heat pumps to deliver heat at up to 150 °C – thus covering the great majority of steam demand in the examined sectors – requires this ratio to be below 2, which under the low price scenario (without taxes and levies) adopted in this study is expected in the late 2030s.

However, electrifying processes at temperatures that heat pumps are not currently able to achieve – for example those that require heat above 165 °C[8] – may only become competitive at a lower electricity-to-gas price ratio, closer to 1. This is the case with electrode boilers, which can reach medium temperatures beyond the capabilities of heat pumps. In these cases, using electric appliances flexibly – e.g. by integrating storage and hybrid systems – can make electrification more cost effective as electric appliances would be used during periods of cheap and abundant electricity supply. Consequently, at least partial electrification (if a hybrid system were used) could be economically advantageous even at a generally high electricity-to-gas price ratio (e.g. one calculated on a biannual or annual basis).

Due to the limited efficiency gains they offer by comparison with new fossil installations, scenarios involving a high level of hydrogen deployment show higher costs. More favourable assumptions about hydrogen prices could potentially affect the results but would need to be below EUR 65/MWh to challenge the findings. Showing a direct comparison of the technologies, Figure 10 clearly illustrates the economic advantages of electrification technologies when electricity prices are low and gas and CO_2 prices are rising. Hydrogen technologies do not entail this advantage over fossil technologies.

Second, while direct and indirect electrification could both achieve fully decarbonised process heat, direct electrification does so with lower cumulative emissions (-24 to -74 Mt CO_2). The fastest emission reduction (including electricity grid emissions) is achieved when heat pumps are used extensively, yet all technology mixes aimed at direct electrification follow similar trajectories. Unless green hydrogen becomes available much sooner than this study expects, its use is not likely to start lowering emissions before 2030. This will result in higher

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[8] It is estimated that industrial heat pumps could reach temperatures of up to 300 °C by 2035 [5].

cumulative emissions – as fossil installations will have their lifetimes extended and may see reinvestment – and a much steeper reduction path after 2040.

The third aspect investigated concerns efficiency and the possibility to reduce fossil fuels usage. Using heat pumps to electrify process heat can achieve substantial savings and reduce dependence on fossil fuel imports. Since hydrogen will not be available in sufficient quantities in the coming years, dependence on fossil fuels will initially increase in the hydrogen-focused scenarios and is generally subject to uncertainty regarding price and infrastructure. Electrification already offers efficiency advantages today, but these will become increasingly apparent in the future if the temperature range of heat pumps is expanded.

The current policy framework is generally consistent with heat pumps being used to electrify processes requiring low temperature process heat, provided that a favourable fiscal environment for electricity and a gradual increase in the carbon price are sustained. However, the electricity-to-gas price ratio needs to decrease more rapidly in the short term to support the electrification of processes requiring medium-temperature heat. Widening the favourable fiscal treatment of electricity for SMEs and introducing a grid charge regime that is more conducive to flexible electricity consumption can greatly help ensure that electric appliances are deployed across the entire low- and medium-temperature heat range. A lack of incentives in the short term may prompt companies to reinvest in fossil heat appliances, thereby locking in technological pathways that entail higher costs, higher emissions and continued dependence on imported fossil fuels.

To support the transition, barriers such as restricted grid connection capacity should be addressed and the price ratio of electricity to fossil gas should reach a competitive level. All these measures can have a high and immediate impact because technological solutions are already available and can, given the right market conditions, avoid reinvestment in fossil installations.

5 Case study: Italy[9]

5.1 Sectoral scope

The Italian manufacturing industry is the second largest in Europe and the eighth largest in the world.[10] In 2021, industry accounted for approximately 22 percent of Italy's direct GHG emissions, equating to 85.4 Mt CO_{2eq}[11]. 63 percent of industrial emissions were the result of directly burning fossil fuels (primarily fossil gas[12]) to produce heat in industrial processes.

This case study draws on an analysis undertaken by ECCO to assess the potential for directly electrifying industrial process heat in Italy[13]. The analysis focuses on sectors offering the greatest and most immediately exploitable potential, such as those falling under the scope of the Effort Sharing Regulation (ESR). Based on the literature data[14], total heat consumption under 150 °C accounted for 81.4 TWh, with a minimum emission reduction potential of 8.3 Mt CO_2[15] by 2030. Low- to medium-temperature process heat electrification under 150°C is primarily used in specific subsectors, such as the food and beverage, pulp and

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[9] Based on ECCO (2025).

[10] UNIDO data for 2022, measured in US dollars at constant 2015 prices

[11] ECCO elaboration based on UNFCCC dataset 2022. The share rose to 31% when emissions resulting from electricity use were considered.

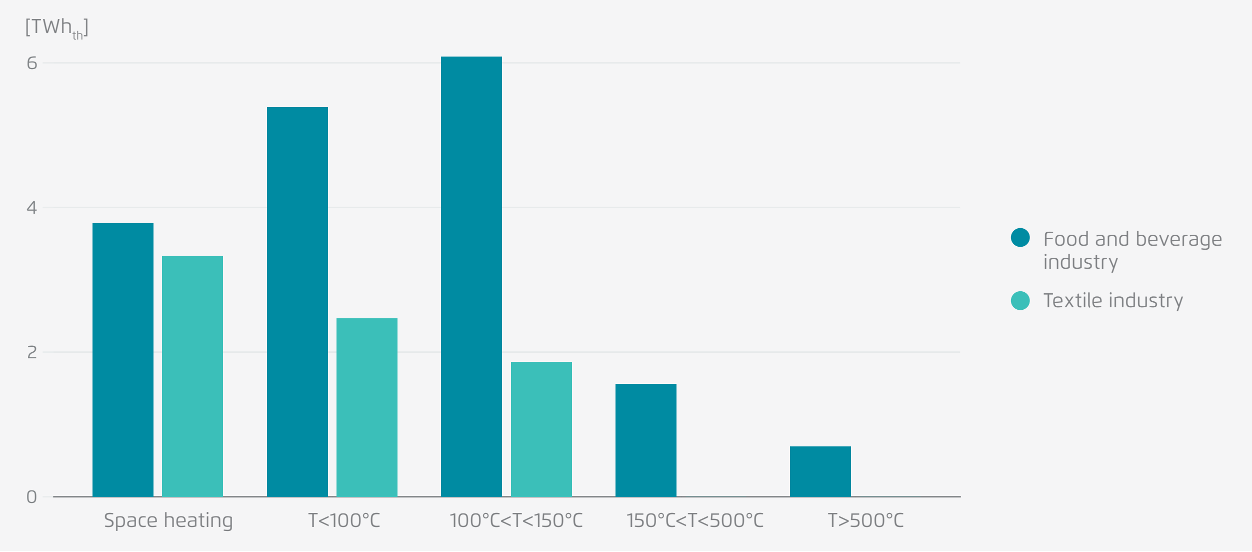
[12] In 2021, natural gas accounted for 39% of the final energy consumption within the industrial sector. ECCO elaboration based on Eurostat energy balance Industry 2022 and UNFCCC database.

[13] Industry and electrification, strategic opportunities for the National Energy and Climate Plan, ECCO, 2024

[14] Data refer to 2021. ECCO elaboration based on Kosmadakis, Georg; "Estimating the potential of industrial (high temperature) heat pumps for exploiting waste heat in EU industries", Applied Thermal Engineering, 20 April 2019, Applied Thermal Engineering, 25 June 2018.

[15] Assuming that 50% of such heat is electrified by 2030 and that natural gas is solely responsible for all heat consumption, which is a conservative estimate.

Heat demand in the food and beverages and textile industries in Italy, 2021 → Fig. 20



ECCO Think Tank (2025)

paper, textile, leather and machinery sectors. Heat in these sectors is mainly required in the form of hot water and steam for use in industrial processes.

This study focuses on two key sectors of the Italian manufacturing industry: the food and beverage and the textile sectors (Figure 20). These are characterised by their substantial use of low- and medium-temperature process heat and their low heat demand, accounting respectively for nine and three percent of industrial process heat demand in Italy. However, the processes in question are representative of a heat range that is also widely used in other sectors.

5.1.1 Food and beverage sector

In 2021, Italy's **food and beverage sector** had a final energy consumption of 39 TWh of energy and generated 4.2 million tonnes of direct CO_{2eq} emissions. 30 TWh of the total energy consumption was used for process heat. 73 percent (21.9 TWh of thermal energy) of process heat demand is covered by fossil gas-based technologies, 32 percent (9.6 TWh of thermal energy) by electricity and the remainder by fuel oil. In this study, the following sectors are in scope:

- **Steam processes**: In 2021, steam processes such as pasteurisation, sterilisation and distillation accounted for the lion's share of the food and beverage sector's energy demand, namely 71 percent. Steam is primarily generated by burning fossil gas in boilers or CHP units. Boilers cover 73 percent of the energy supply and CHP units 20 percent with the remaining energy being supplied by other boilers (mostly fuel oil and biomass boilers).
- **Drying processes**: Drying processes account for 12 percent of the sector's energy consumption. These include steam drying, which uses temperatures of up to 150 °C and is mainly powered by fossil gas boilers and CHP units; thermal drying, which operates at lower temperatures (below 80°C) and is supplied by fossil gas (92 percent) and fuel oil boilers; direct heat drying, accounting for ten percent of total energy demand, is primarily powered by electric technologies such as infrared or microwave systems.
- **Oven processes**: Oven processes also account for 12 percent of energy demand and can reach temperatures as high as 250 °C. While these processes have historically been fuelled entirely by fossil-based technologies, electric ovens have steadily become more popular, covering 57 percent of the energy supply in 2021. The remaining energy is provided by fossil gas ovens (38 percent), fuel oil ovens (7 percent) and microwave technologies (2 percent).
- Other specific heat processes, which account for five percent of energy demand, operate at temperatures below 150 °C. These are primarily supplied by electric appliances, with the remainder supplied by fossil gas and a minor share by fuel oil.

5.1.2 Textile industry

Final energy consumption in the **textile sector** amounted to 12 TWh[16] in 2021 and generated 1.4 million tonnes of direct CO_{2eq} emissions. Process heat accounted for 73 percent (8.5 TWh) of total energy consumption. 65 percent of process heat was supplied by gas (5.5 TWh_{th}), 28 percent by electricity (2.4 TWh_{th}) and 5 percent by fuel oil.

The sector's heat demand can be categorised[17] as steam processes, which account for 69 percent of the energy demand – including pre-treatments, wet processing and steam drying – and non-steam drying processes:

- **Steam processes**: Steam processes can reach temperatures of up to 180 °C, depending on the pressure needed for the specific processes and materials manufactured. For example, dyeing synthetic fibres can require temperatures as high as 130 °C, while natural fibres require 100 °C. The energy demand for steam processes is primarily met by

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[16] Aggregated data with textiles and leather.
[17] ECCO's elaboration on JRC IDEES database 2024

fossil-based technologies, with fossil gas boilers accounting for 87 percent of the energy share, fuel oil boilers for 8 percent and CHP for 5 percent.

→ **Thermal drying**: Thermal drying, which operates at temperatures below 80 °C, primarily relies on fossil fuel technologies. In contrast, direct heat drying, the largest contributor to energy demand among the drying processes (62 percent), is achieved using microwave appliances, making this sub-process fully electrified.

5.2 Scenarios

The aim of this scenario analysis is to understand how energy market fundamentals and select policy interventions influence the business case of adopting direct electrification technologies in the food and beverage and textile sectors in Italy between 2025 and 2050. The main objective is to contrast the electrification pathway with scenarios involving continued reliance on fossil fuels or the potential use of biomethane as a primary decarbonisation pathway for the sectors in question. In addition, a policy and market sensitivity analysis is performed. Three commodity price scenarios were assumed on the basis of the wholesale electricity price plus ETS2, including transmission and distribution fees.

5.2.1 Scenario construction

Main market scenarios

Business as usual (BAU) scenario: This scenario projects the current energy price conditions and the policy context over the considered timeframe. Its purpose is to explore whether direct electrification can outcompete fossil heat solely based on CAPEX and efficiency gains. Energy prices remain constant throughout the selected timeframe, replicating the average data from 2010 to 2020, to prevent results from being affected by the extreme volatility observed in recent years. Electricity and gas prices for the selected sectors were collected from the Italian Regulatory Authority and the Manager of Energy Services (GME) and reflect the costs for SMEs, including transmission, distribution and ETS charges on electricity. Under this scenario, ETS2 is not included in the gas price so as to reflect current conditions and the possibility of a reversal in carbon pricing policies.

Electrification scenario: This scenario entails a gradual decrease in the spark gap between electricity and gas prices and envisages price parity in 2042. The wholesale gas price is projected according to the National Energy and Climate Plan (NECP), adding transport and distribution charges and the evolution of the ETS2 charge. The electricity price includes transport, distribution and ETS charges and is progressively decoupled from gas, reaching the levelised cost of electricity (LCOE) of a PV generation system with storage by 2050. The scenario explores the adoption of electrification,considering the expected evolution of commodity prices, including the ETS and ETS2 charges and a gradual decoupling of electricity price from gas based on a linear reduction in the number of hours when gas sets the power prices at the margin. Overall, the assumed prices are based on the continued implementation of carbon pricing and renewable energy deployment.

Biomethane scenario: This scenario explores the potential adoption of biomethane-based solutions for decarbonising the sector's heat demand. To promote biomethane-based technologies, the biomethane price in this scenario was presumed to be subsidised via incentives that result in a raw cost comparable to that of fossil gas. The prices of gas and electricity are projected as per the electrification scenario. The scenario explores the conditions required for a competitive uptake of biomethane as a key source of process heat in the sectors under consideration, reflecting sustained policy support for biomethane.

Policy and market sensitivity scenarios

Given that the three previous market scenario assumptions do not account for industry inertia or any potential delays in responding to favourable commodity prices for adopting electrification, it was deemed necessary to evaluate possible policy measures that could accelerate electrification. Two policy measures were simulated for the electrification scenario, resulting in **two policy sub-scenarios**.

Electrification scenario + depreciation incentive: The objective of the analyses is to simulate a policy aimed at reducing the cost of capital for new technologies and at incentivising efficiency. The weighted average cost of capital (WACC) is therefore decreased from ten to four percent. This measure is intended to incentivise companies to invest in more new technologies to replace existing ones. In this case, all new technologies, whether gas- or electricity-based, are incentivised. This scenario adopts the same while price assumptions of the electrification scenarios. As such, this scenario represents a technologically neutral incentive.

Electrification scenario + depreciation incentive + CAPEX discount: These analyses aim to simulate targeted policies for electrification. In addition to the depreciation policy scenarios, the investment costs of electrification technologies are discounted by 50 percent until 2040 to simulate direct incentives for electrification.

Finally, a sensitivity analysis is performed. Given the volatility associated with gas prices, it was deemed necessary to **subject gas prices to a sensitivity analysis** for the electrification scenario in order to assess how convenient electrification appears when considering more conservative gas price projections.

The CAPEX and energy price assumptions for each scenario are summarised in Annex 2, Tables 10–11.

5.2.2 Methodology

The scenarios were generated using a cost-optimisation model for long-term energy planning, developed specifically for this study using the open-source software Osemosys[18]. This tool enables computational analysis to determine the minimum cost required to satisfy a defined energy demand (defined by commodities, such as heat) using a set of available technologies characterised by parameters such as investment costs and efficiency. Each technology simulates the conversion of primary into secondary commodities (e.g. gas boilers convert gas into heat), with the costs of commodity consumption factored into the operational costs of the technology. The model identifies the most cost-effective solution (i.e. the optimal set of technologies) over the entire modelled timeframe from 2021 to 2050. The modelled sectors' energy consumption in 2021 was replicated on the basis of the IDEES database[19], which offers detailed data on sector-specific energy consumption and demand by industrial process. Over the timeframe, new technologies can replace existing ones, reflecting technological innovation.

Three scenarios were constructed on the basis of the following *assumptions*:

- → Commodity price projections: These are the primary assumptions upon which this scenario analysis is based. To provide different insights, different projections of the wholesale prices of electricity and gas, including ETS, transmission and distribution charges from 2021 to 2050, were developed (Annex 2, Table 11).
- → Technological investment costs (CAPEX): In line with the JRC IDEES database, the technologies currently used by the sectors for each process were mapped. In addition, the model included technologies that are either currently available or expected to be available in the future to meet the energy demand of the respective processes. Their price projections were defined by researching the relevant literature and engaging in discussion with relevant stakeholders. The initial price of the technologies is set to decrease over time due to market adoption, especially in the case of heat pumps for industrial applications (Annex 2, Table 10).

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[18] http://www.osemosys.org/

[19] IDEES Database- Italy industry, 2024, JRC

→ Heat demand projections: All scenarios were based on the heat demand of industrial processes in 2021. Demand levels were projected until 2050 using the gross value added (GVA) growth rate as the driver, as indicated in Italy's National Energy and Climate Plan (Ministero dell'Ambiente e della Sicurezza Energetica 2024).

→ Technological efficiency: To represent technological innovation and improvement, existing and newly available technologies were characterised by increasing efficiency, based on sector literature and interviews with relevant stakeholders during dedicated meetings (Annex 2, Table 10).

→ Grid energy mix: To forecast the share of renewable sources in the Italian electricity mix, the estimates contained in the National Energy and Climate Plan (Ministero dell'Ambiente e della Sicurezza Energetica 2024) were adopted[20]. The mix of non-renewable sources was estimated on the basis of previous studies (Artelys and ECCO Think Tank 2023). This share is used to calculate primary energy consumption across the different scenarios, taking into account the relative efficiencies of energy production processes[21] (Annex 2, Table 12).

In addition, the scenarios share the following *primary functions*:

→ **Competitive optimisation**: The model assesses multiple technology options, selecting the least and most cost-effective solutions according to the given conditions. No constraints were imposed on the maximum installed capacities per year, making the model sensitive to variations in commodity prices and CAPEX costs of technologies. This is because this study does not aim to simulate the industry's inertia in adopting electrified solutions but to illustrate a scenario that reflects *when* favourable conditions for the full uptake of electrification are in place.

→ **Modes of operation:** The model reflects the complexity of the sectors' processes by defining temperature-specific technology demand (e.g. a boiler can produce steam or water at >150 °C, while low-temperature heat pumps can only produce water at <80 °C) and by allowing multiple operating modes from which the model selects to meet heat demand in each unit of time (e.g. boilers only produce steam in one unit of time because only steam is in demand at that time; in the next unit of time they produce steam and water >150 °C to meet the demand for both, while in the next unit of time they produce only water at >150 °C).

→ **Weighted average cost of capital (WACC):** To reflect the problems that Italian industry faces in accessing financing for non-core activities (i.e., energy efficiency) the analysis assumes a WACC of ten percent.

CO_2 emissions are calculated by applying CO_2 intensities to the energy carriers. The indirect emissions incurred when electricity and hydrogen are used to generate heat are also taken into account.

The primary energy consumption was calculated for each year based on the technology mix and expected efficiency gains in the different scenarios, as well as on the developments in the Italian power mix. Ambient heat was not included in the primary energy calculation.

5.3 Results

5.3.1 Cost-optimal technology mix

Assuming that historical price and policy dynamics continue (BAU scenario), limited electrification of Italy's food and beverage and textile sectors is envisaged (Figure 21). Gas boilers remain the most competitive solution in steam processes. Existing capacity is gradually replaced by more efficient – though still fossil gas-based – technologies, while CHP systems are phased out at the end of their lifetime to reflect a gradual phase-out of fossil fuels in the electricity market. Heat pumps are gradually deployed only

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[20] The NECP provides estimates until 2040, ECCO assumed fully renewable electricity by 2050, in line with the Green Deal objectives

[21] Efficiencies assessed from: World Energy Balances (2024), IEA family and beyond Database documentation

in processes requiring temperatures below 80 °C, outcompeting the new hot water gas boilers. This is because they are highly efficient, which offsets the unfavourable price of electricity compared to gas. In the food and beverage sector, high-temperature heat pumps are also installed in 2050 to meet 30 percent of the specific heat demand at temperatures above 80 °C. Uptake of these heat pumps occurs at a later stage of the simulation due to their initially higher CAPEX.

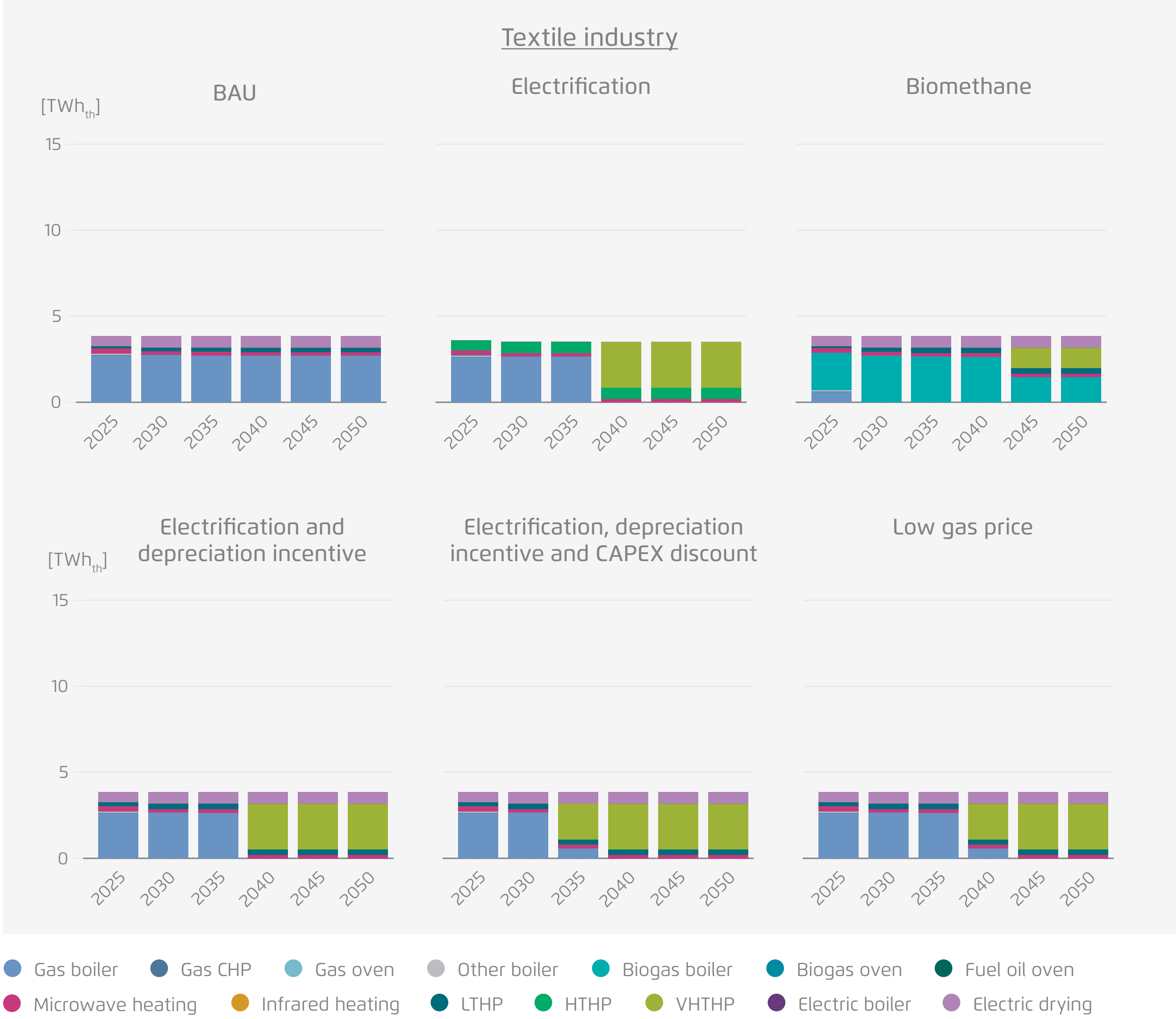
Under a scenario in which the spark gap between electricity and fossil gas (including ETS costs) is gradually reduced (and closed in 2042 (electrification scenario)), full electrification is achieved in the considered sectors by 2040 (Figure 21). In other words, electrification is achieved when the spark gap reaches 1.1. In processes below 80 °C, heat pumps outcompete gas boilers by 2025, supplying 100 percent of the heat required at these temperatures in both sectors. For steam-based processes, the model adopts new gas steam boilers between 2025 and

Heat technology mix by scenario, Italy → Fig. 21a

ECCO Think Tank (2025)

Heat technology mix by scenario, Italy

→ Fig. 21b



ECCO Think Tank (2025)

2035, which are later substituted by electric alternatives. By 2040, heat pump systems with boosters, in conjunction with electric boilers, cover the entire demand for steam in the textile sector and most of the steam demand in the food and beverage sector. Electric boilers remain in the technology mix despite being less efficient, because of the high capacity of heat pumps with boosters required by the food and beverage sector. This, combined with heat pumps' substantial CAPEX, drives up the system costs compared to electric boilers.

In the biomethane scenario, efficient biomethane boilers outcompete gas boilers because it is assumed that subsidies will cover the gap with fossil gas, which remains in place despite the disadvantage of fossil gas due to rising carbon costs under ETS2. Even in this scenario, heat pumps substitute existing technologies in processes at temperatures below 80 °C (Figure 20). Because a low electricity price is assumed, heat pumps with booster systems also appear in the mix between 2045 and 2050.

Based on the prices projected in the electrification scenario, Figure 21 illustrates how cost-optimal technology pathways evolve when depreciation incentives and CAPEX support are introduced in the food and beverage sector. Supportive policies allow companies to start electrifying their steam processes five years earlier, accounting for 86 percent of the heat mix by 2035. Furthermore, the results show how the most efficient technologies, predominantly heat pumps, are prioritised. Similar trends are observed in the textile sector (Figure 21): when depreciation incentives are factored into the equation, the uptake of heat pumps is brought forward by four years. From 2036, heat pumps with booster systems supply 44 percent of the heat required by steam processes. If depreciation incentives and CAPEX discounts for energy-efficient technologies are considered, heat pumps with boosters are expected to be introduced by 2035, covering 77 percent of the heat demand for steam processes. In both sectors, low-temperature heat pumps remain the most convenient option for non-steam processes.

Given the uncertainties associated with future projections of fossil gas prices, a market sensitivity analysis based on a more conservative gas price projection is conducted. The declining gas price is expected to bring the crossover point between electricity and gas prices forward by approximately five years, compared to the electrification scenario. Complete electrification of process heat is therefore achieved in the food and beverage sector in 2048 and in the textile sector in 2044. Heat pumps are still identified as the most cost-effective technology in processes below 80 °C as of 2025, as in the previous scenario, while steam processes are only electrified after 2045. Full electrification is reached by installing heat pumps with boosters plus, in the case of the food and beverage sector, electric boilers. In 2050 the technology mix in the two sectors is similar to that in the electrification scenario (Figure 21). The results make it clear that the projected ETS2 prices and gradual increase in electricity from renewable sources are expected to favour electrification in the sectors in question even at lower fossil gas prices.

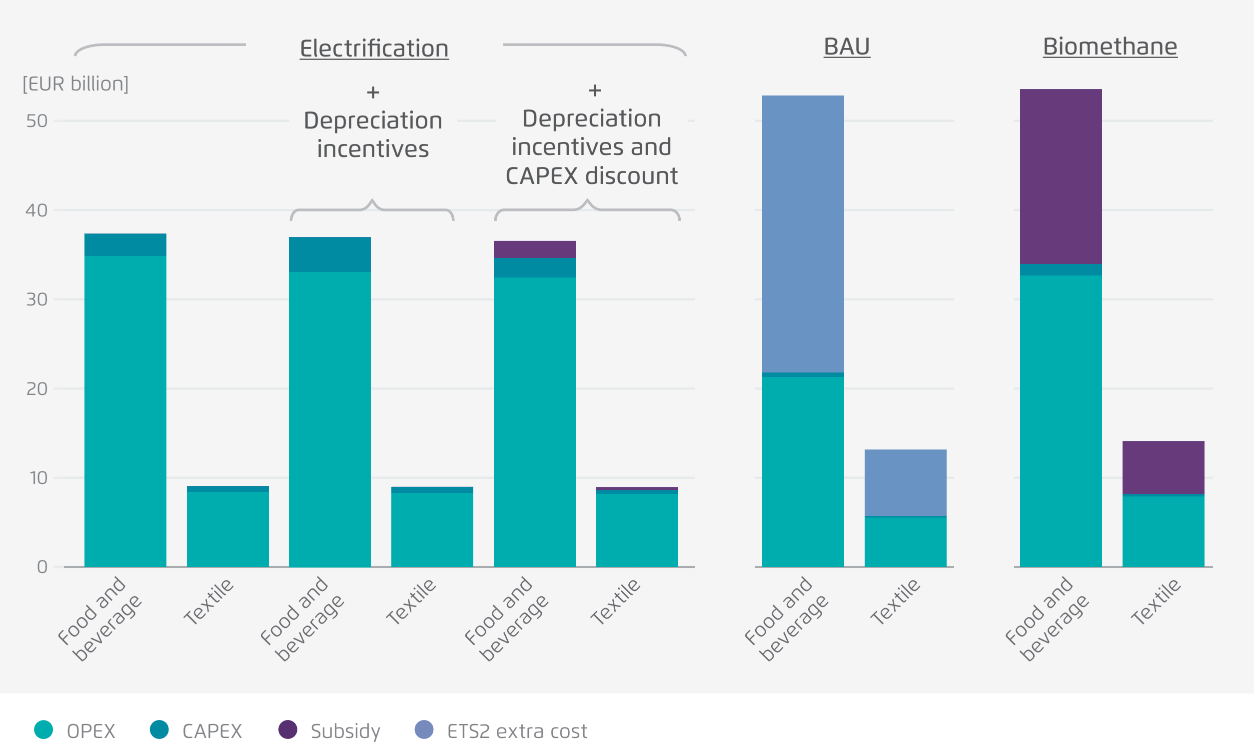
5.3.2 Cumulative cost assessment

The cumulative operational costs of the BAU scenario (2025–2050) amount to 21.3 billion euros (EUR) in the food and beverage sector and EUR 5.6 billion in the textile sector. The respective CAPEX costs total EUR 0.53 billion and EUR 0.18 billion, resulting in a levelised cost of heat (LCOH) of EUR 58.1/MWh (food and beverage sector) and EUR 49.92/MWh (textile sector). However, these figures may not accurately reflect the actual costs of the scenario. The ETS2 price levied on fossil gas is expected to drive up the operational costs of the simulated technology mix. By simulating the same mix of technologies and accounting for the ETS2 price and the associated increase in electricity costs due to the coupling of electricity and gas prices, overall operational costs are estimated to rise to EUR 52.3 billion in the food and beverage sector and EUR 13 billion in the textile sector. This would increase the LCOH to EUR 140.7/MWh and EUR 114/MWh respectively (Figure 22).

The cumulative operational costs of the electrification scenario (2025–2050) amount to EUR 34.9 billion in the food and beverage sector and EUR 8.4 billion in the textile sector, while the respective CAPEX costs total EUR 2.5 billion and EUR 0.6 billion, leading to an LCOH of EUR 99.4/MWh (food and beverage sector) and EUR 78.6/MWh (textile sector).

The cumulative operational costs of the biomethane scenario (2025–2050) amount to EUR 32.7 billion in the food and beverage sector and EUR 7.9 billion in the textile sector. The respective CAPEX costs total EUR 1.3 billion and EUR 0.3 billion, resulting in an LCOH of EUR 90.3/MWh (food and beverage sector) and EUR 71.4/MWh (textile sector). Considering the estimated prices of biomethane, the subsidies required to enable the market uptake of biomethane-based technologies amount to EUR 19.6 billion in the food and beverage sector and EUR 5.9 billion in the textile sector. Without these subsidies, the LCOH resulting from the scenarios could reach EUR 142/MWh in the food and beverage sector and EUR 122/MWh in the textile sector. Given the low availability of biomethane, subsidies will most likely end up supporting gas-intensive industries. Consequently, the

Cumulative costs by scenario and selected sectors in Italy, 2025–2050 → Fig. 22



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overall cost of a biomethane-based decarbonisation pathway is expected to be significantly higher than in the other scenarios, thus failing to compete with gas and electric solutions.

Operational costs are reduced by the assessed policy incentives as shown in the figure below (Figure 22). Factoring depreciation incentives into the equation decreases the LCOH to EUR 98.3/MWh in the food and beverage sector and to EUR 78.1/MWh in the textile sector. If CAPEX discounts are also considered, the respective LCOH is EUR 92/MWh and EUR 75/MWh. The total cost of these subsidies amounts to EUR 1.9 billion for the food and beverage sector and EUR 0.3 billion for the textile sector. Without subsidies, CAPEX costs would total EUR 4.1 billion (an 86 percent increase) for the food and beverage sector and EUR 0.72 billion (a 71 percent increase) for the textile sector.

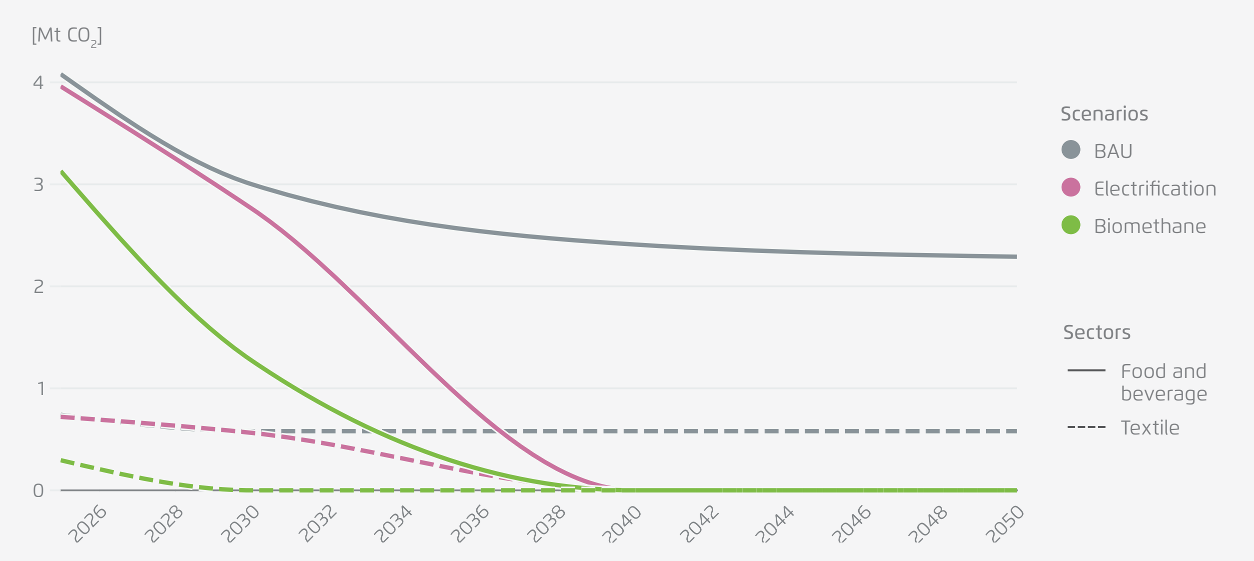
5.3.3 Emission assessment

Under the BAU scenario, the sectors in question are not fully decarbonised. However, direct emissions in both sectors are expected to decrease by approximately 50 percent (compared to the 2021 level) by 2050 as all technology options, including gas boilers, become increasingly efficient. Electric technologies reduce emissions by 1.7 Mt CO_2, with the remaining reduction coming courtesy of the improved efficiency of new gas boilers, bringing gas consumption down by almost 50 percent by 2050 compared to 2021.

The electrification scenario achieves full decarbonisation of the two sectors by 2040. Until 2030, emission reductions are driven primarily by the increased efficiency of new gas boilers. Thereafter, direct electrification is responsible for further reducing and eliminating emissions (Figure 23).

CO_2 emissions by decarbonisation scenario and selected sectors in Italy

→ Fig. 23



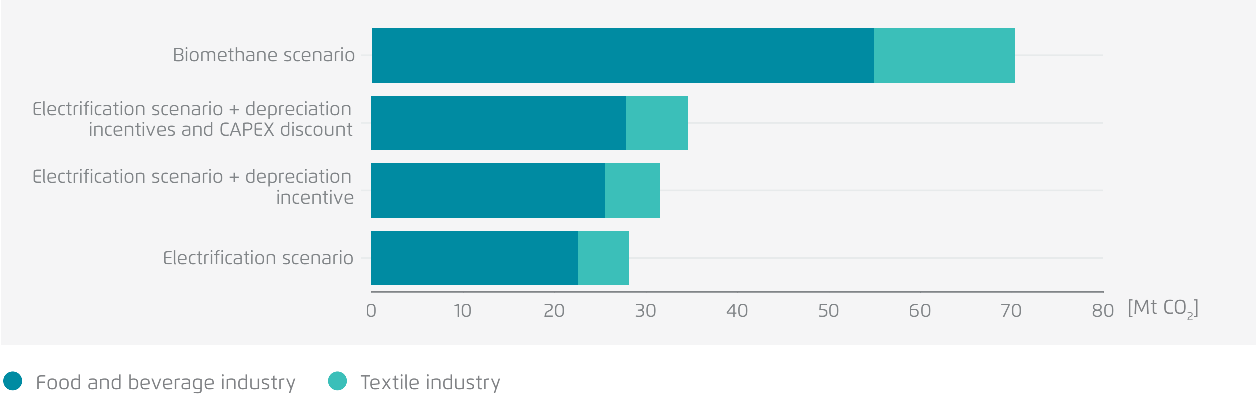
Agora Industry elaboration of ECCO Think Tank data (2025)

The biomethane scenario also reduces direct emissions to zero by 2040. Existing technologies are replaced by new biomethane-based systems more quickly in the textile sector, allowing it to decarbonise by 2030 (Figure 23).

The analysis of cumulative emissions (including both direct and indirect emissions) reveals that the electrification scenario has an advantage over the BAU scenario. This could even be increased if policy incentives were made available to support earlier uptake of heat pumps (Figure 24). However, this advantage is less pronounced than in the German case study, largely because of the extended role that gas plays in Italy's power mix, which increases the relevance of indirect emissions from the power sector. The biomethane scenario reveals the highest cumulative emissions advantage, but only assuming the substantial subsidisation discussed in Section 5.3.2.

Cumulative CO_2 emission savings compared to the BAU scenario by decarbonisation scenario and selected sectors in Italy, 2025–2050

→ Fig. 24



ECCO Think Tank (2025)

5.3.4 Primary energy consumption and fossil fuel savings assessment

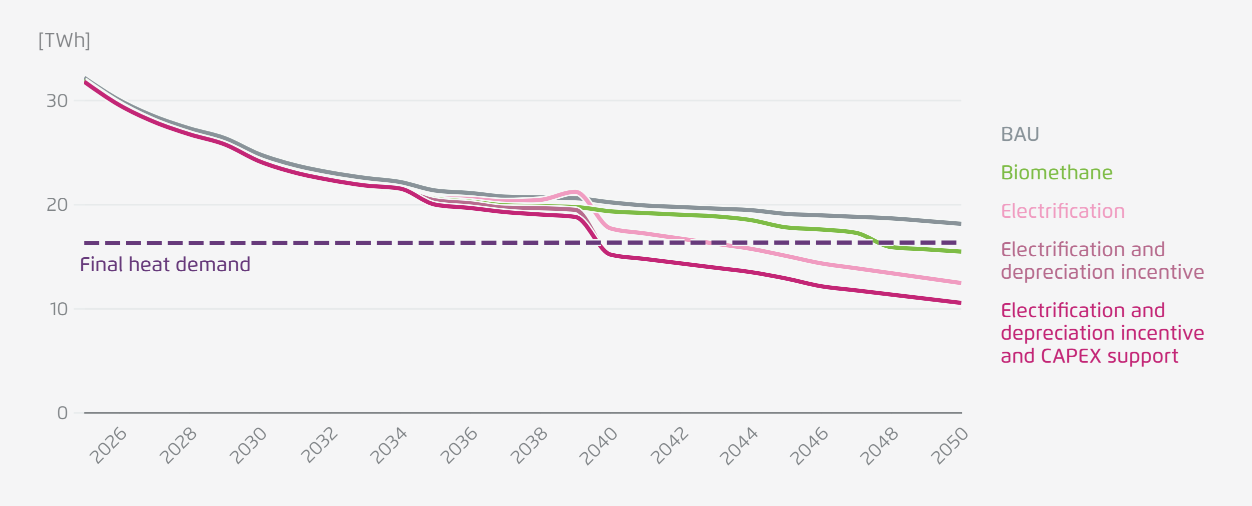
As all appliances become increasingly efficient, primary energy is on a downward trend across all scenarios and shows limited divergence until the mid-2030s. Thereafter, the electrification scenarios start indicating considerably higher primary energy savings than the BAU and biomethane scenarios based on molecules, largely because heat pumps are deployed more quickly and the power mix is gradually defossilised . The earlier adoption of heat pumps facilitated by the simulated policies means that primary energy consumption falls below final heat demand before 2040; without this policy push, primary energy consumption only drops below final heat demand in around the mid-2040s (Figure 25).

In cumulative terms, the biomethane scenario delivers higher fossil energy – and especially fossil gas – savings than the electrification scenario, largely due to the protracted role played by fossil gas in the Italian power mix. Under the BAU scenario, the primary energy consumption of fossil gas in 2050 is 11.42 TWh in the food and beverage sector and 2.86 TWh in the textile sector, down on 2021 levels by 55 percent and 60 percent respectively. This is mainly the result of improving the energy efficiency of fossil-based technologies and greening the electricity grid.

Over the simulated period, the sectors directly consume 28.5 billion cubic metres (bcm) of biomethane, avoiding approximately 62.6 Mt of direct CO_2 emissions. However, the feedstock required to produce the biomethane envisaged for this scenario may not be available. National and European organisations project Italian biomethane outputs of 5.8 bcm by 2030 and 14.5 bcm by 2050 (European Biogas Association 2024). In 2023 however, despite national incentives being provided to produce 1 bcm of biomethane, only 35 percent of this figure was achieved. Considering that final biomethane consumption across the sectors in the scenario is approximately 0.96 bcm in 2030 and 0.88 bcm in 2050, representing 17 percent and 6 percent of the projected theoretical yield respectively, it seems unlikely that such a significant share of biomethane will be allocated to sectors which are not considered "hard to abate", especially if actual production fails to meet government projections.

Primary energy consumption in selected sectors' low- and medium-temperature processes in different scenarios in Italy

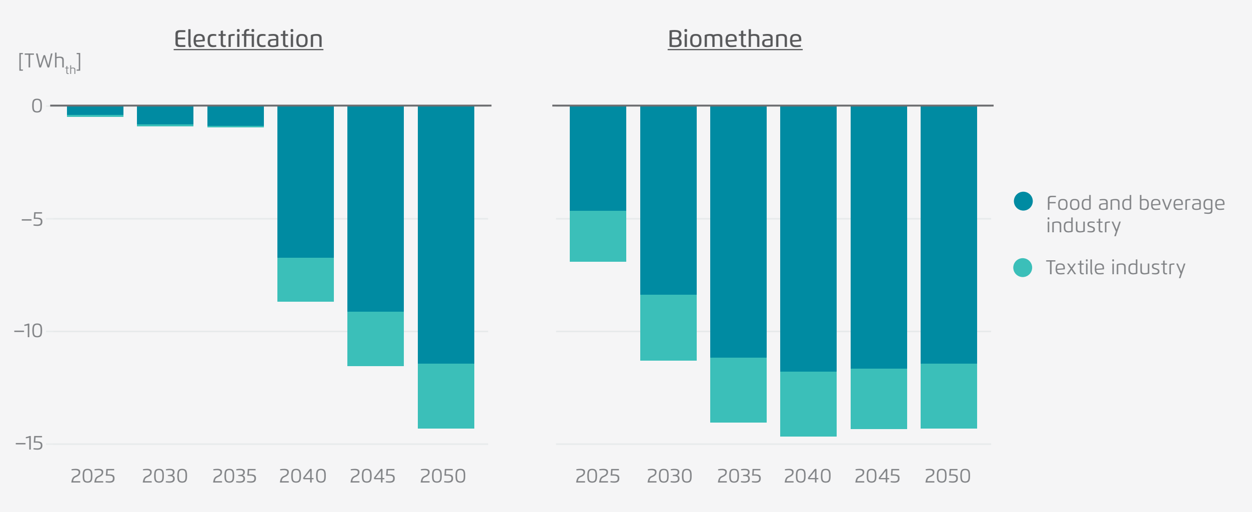
→ Fig. 25



Agora Industry elaboration of ECCO Think Tank Data (2025)

Avoided fossil energy demand in the electrification and biomethane scenarios in selected industrial sectors in Italy

→ Fig. 26



Agora Industry elaboration of ECCO Think Tank data (2025)

Static analysis of selected applications in the Italian food and beverage and textile sectors

Six case studies were analysed to assess the feasibility of electrification using technologies readily available on the market and identify possible barriers to their application. The case studies were provided by a technical partner and supplemented by information collected from discussions with partners and stakeholders, as well as from questionnaires distributed to Italian businesses in the selected sectors.

All case studies were based on 2023 commodity prices: EUR 0.5/cm for fossil gas, EUR 0.25/kWh for electricity and EUR 73/t CO_2 for the EU ETS allowances. Unlike the scenario analysis, these prices included fiscal and parafiscal contributions, such as general system charges, excise duties and VAT.

In the **food and beverage industry**, four different case studies were conducted, involving three dairy industries and one brewery.

The first dairy plant produces approximately 100,000 Grana Padano DOP wheels annually and processes around 47.5 million litres of milk. The cooking phase, which currently requires low-pressure steam at approximately 55 °C, accounts for around half of the company’s heat demand. The remaining heat demand is generated by less energy-intensive processes that require hot water at temperatures of between 80 °C and 85 °C. The facility’s thermal power plant consists of two steam boilers with a capacity of 2 MW each. The study assumed that the current steam boilers would be replaced by two 200 kW heat pumps, using the available waste heat from the condensation from the chillers to supply heat at 85 °C and a 250 kW electric boiler to generate steam.

The second dairy plant is a medium-sized enterprise producing Italian soft cheeses (taleggio DOP, quartirolo DOP) and processing approximately 35 million litres of milk per year. The plant's main heat demand is met by a fossil gas boiler that supplies approximately 4.2 GWh per year.

The steam used at this dairy plant is almost completely avoidable and could be replaced with water at a temperature of 85°C. The only non-replaceable use is when steam is injected directly into the multipurpose unit to produce quartirolo DOP cheese, which occurs on a limited number of days per week. It is assumed that demand for this specific steam-based process could be met using an electric steam boiler (1 MW). The remaining heat demand (equating to 80 percent of the annual demand) can be met with a 1 MW heat pump.

The third case study involves a large industrial dairy plant that produces 50,000 tonnes of soft cheese annually. The industry's heat demand is currently met by three fossil gas boilers and two CHP units that supply approximately 50 GWh of thermal energy per year. The following technology mix was considered to electrify this plant:

- one heat pump of 550 kW (60 °C) powered by recovery heat from chilled water (8–19 °C)
- one heat pump of 2.5 MW (80–90 °C) powered by condensation heat from the chillers (available at 30 °C)
- one heat pump of 4 MW (70 °C) powered by external air
- one electric boiler of 1 MW to meet the remaining demand for high-temperature heat (superheated water or steam).

Across all the analysed cases of dairy industries, overall energy demand is spread evenly throughout the year with no significant seasonal shifts. Nonetheless, most heat-intensive processes (cooking, pasteurisation, sterilisation) typically occur during the morning, with peak activity taking place between 6:00 and 14:00.

In the case of the beverage industry, a medium-sized industrial brewery producing 1,000,000 hl/year was analysed. Several processes within the brewery require different heat inputs at different temperatures, ranging from low to medium. The most heat-intensive processes include boiling malt, which reaches temperatures of 108 °C, and the pasteurisation of bottles, which reaches 70 °C. At present, heat is supplied by fossil gas boilers, which generate 20 GWh annually.

In this case study, 50 percent of the thermal energy demand could be met using heat pumps, leveraging the waste heat from the cooking process and the excess heat from the refrigerators as heat sinks.

As far as the supply of steam is concerned, two alternative ways of producing steam were assessed, the first based on electric boilers and the second using biomethane boilers – the latter because the plant generates 20 tonnes of crop residues annually which could be used to produce biogas through anaerobic digestion.

Two case studies were assessed in the **textile sector**. Both related to the wool industry, with each producing around 2,500 tonnes of wool fabric annually. In both cases, thermal energy is generated using gas boilers that produce steam at 9 bar and 175 °C. The annual heat demand for the industries is 11.25 GWh in the first case study and 19.8 GWh in the second case study. The level of plant production remains constant throughout the year, with daily fluctuations. Most of the energy consumption occurs between 6:00 and 18:00.

The plant in the first case study is dedicated solely to dyeing textiles, with temperatures ranging from 70 to 120 °C. The dyeing process requires precisely controlled temperature ramps, which are achieved by using steam to heat water steam. The water used in the process is extracted at around 35–40 °C, treated to remove chemical substances and then discharged.

The proposed solution involves installing a 460 kW heat pump that recycles heat from the wastewater of the dyeing process. The generated heat is used to preheat the tank from which the dyeing machinery draws water, raising the tank temperature from 35 °C to 50 °C and thereby reducing the thermal load needed from the steam. An electric boiler was considered for this purpose.

The plant analysed in the second case study has an integrated production process that includes washing, drying and finishing. The proposed intervention includes using infrared dryers to cover eight percent of the heat demand, heat pumps to meet low-temperature demands (<65 °C) using waste heat flows from the dyeing processes as heat sinks, and electric boilers to produce steam. A final share of the heat load demand (three percent), which requires direct firing to achieve a smoother, more uniform surface on the fabric, is deemed non-electrifiable, and no alternatives were considered.

The static analysis shows that it is technically feasible to electrify process heat at medium and low temperatures for nearly all assessed heat flows; however, the electricity price barrier hinders the adoption of electrified solutions compared to gas-based solutions (Tables 4–6).

Main results from the dairy industry static analysis → Table 4

	SME cheese producer	SME cheese and butter producer	Large dairy enterprise
Approx. output [l/y]	46,100,500	35,500,885	600,000,000
Total process heat demand [MWh/y]	2,370	1,202.8	40,000
Steam demand [MWh/y]	1,090	240.6	2,680
Final consumption			
Gas – current [MWh]	2,720	4,924	51,600
Electricity – electrification [MWh]	1,539	2,039	14,745
CAPEX			
Electrification [EUR]	750,000	1,500,000	8,000,000
OPEX			
OPEX – current [EUR/y]	137,287	250,579	2,813,642
OPEX - electrification [EUR/y]	384,737	509,585	3,693,642
ETS1 applies [Y/N]	N	N	Y

ECCO Think Tank (2025)

Results from the beverage industry static analysis

→ Table 5

	Medium-sized industrial brewery
Approx. output (hl/y)	1,000,000
Total process heat demand [MWh]	20,000
Steam demand [MWh]	3,400
Final consumption [MWh/y]	
Gas – current [MWh/y]	22,913
Electricity – electrification [MWh/y]	10,800
CAPEX	
Electrification [EUR]	4,000,000
OPEX	
Current [EUR/y]	1,050,000
Electrification [EUR/year]	3,500,000
ETS1 applies [Y/N]	N

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Results from the textile industry static analysis

→ Table 6

	Wool dyeing enterprise	Wool production enterprise
Total process heat demand [MWh]	11,250	19,842
Final consumption [MWh/y]		
Gas – current [MWh/y]	12,270	21,378
Gas – electrification [MWh/y]	0	608
Electricity – electrification [MWh/y]	10,050	17,120
CAPEX		
Electrification [EUR]	675,000	905,000
OPEX		
Current [EUR/y]	805,000	1,405,000
Electrification [EUR/year]	1,985,000	3,420,000
ETS1 applies [Y/N]	Y	Y

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In all cases, full electrification is not cost competitive given the current fossil gas and electricity prices and fiscal and parafiscal contributions. If prices per kWh are compared, electricity costs five times more than gas. The electric solution therefore requires a COP of or higher than 4.5 to be viable (assuming an efficiency of 0.9 for fossil gas generators). The case studies indicate that the COP depends to a large extent on the conditions under which heat pumps are used, the temperature of the cold source and the flow temperature of the system. However, there is a wide price range within which electrification remains viable at low temperatures (<80 °C). This allows the critical spark gap to be identified between the price of electricity and fossil gas, below which electrification is viable: the spark gap is approximately 3.16 in the case of low temperatures, assuming that the gas boiler will be replaced by a heat pump*; it drops to 1.04 at higher temperatures, assuming that an electric boiler will be used.

It is also possible to assess the impact of the EU ETS price. Full electrification (i.e. whereby the amount of power generated using fossil fuels is reduced to below the 1 MW threshold) eliminates this cost component. The degree to which electrification is viable varies case-by-case, however. This can be illustrated by the example of the large industrial dairy plant: since it is subject to the ETS, the electrification option allows the costs of CO_2 allowances to be reduced. The plant's emissions were estimated on the basis of the thermal energy requirement, assuming an average heat generation efficiency of 95 percent and a fossil gas emission factor of 1.991 kg CO_2/m^3. Over 11,000 tonnes of CO_2 are generated annually. The price of CO_2 allowances is variable and generally increasing. Estimates for the next four years suggest that the price of ETS allowances will be around EUR 85/t $CO_{2,}$ with a further increase expected in the subsequent four years. The savings on environmental allowances therefore amount to approximately EUR 950,000 per year, making the electric option more favourable, though still not able to compete with the reference scenario.

* These values assume a COP of 3 for the heat pump and gas and electric boiler efficiency rates of 0.95 and 0.99 respectively.

5.4 Main takeaways

Considering only wholesale electricity prices and transmission and distribution charges, electrifying processes below 80 °C already appears to be the most cost-effective solution in 2025. This conclusion is based on current technologies, electricity and gas prices, and the absence of supporting policies. However, heat demand below 80 C° only represents approximately ten percent of thermal uses, excluding space heating. Furthermore, the relatively high efficiency of electric technologies for processes exceeding 80 °C is not sufficient to offset their CAPEX costs, which hinders their adoption. At current electricity and gas prices and in the absence of supporting policies, neither full-sector electrification nor decarbonisation are therefore achieved.

All processes become cost-effectively electrified once the electricity price has been progressively decoupled from the gas price, bringing it closer to the LCOE of renewable-based production (i.e. a PV plant with storage) by 2050. Other factors driving electrification include the impact of the ETS2 on gas prices and the progressive decline in investment costs for electric technologies. According to the analysis, this condition is reached between 2035 and 2040. However, the technology mix is not optimal from an energy efficiency perspective, as gas-based options will only be fully replaced by electric alternatives as the electricity and gas price spark gap falls to 1.1. Complete electrification is also achieved if a more conservative projection of gas prices is used.

Polices that favour electrification by providing financial mechanisms and CAPEX cost incentives are still expected to lead to full electrification by 2040. Adopting efficient heat pumps five years earlier points to an electrification rate of approximately 85 percent by 2035 in both sectors, however. Policies lead to cost savings in the long term (Figure 23). According to the analysis, these policies will cost the state 2.3 billion euros between 2025 and 2040. Supportive policies are crucial for addressing the CAPEX costs of electric technologies and accelerating their market adoption.

Biomethane is not expected to compete with electrification as a decarbonisation solution for the food and beverage and textile sectors because its assumed prices are not competitive with gas and electricity. The study estimates that subsidies amounting to 25.5 billion euros are necessary to make its price competitive across the simulated period (2021–2050).

In the absence of subsidies, the overall operational costs in the biomethane scenario would be 50 percent higher than in the electrification scenario for the food and beverage sector and 63 percent higher for the textile sector. Uncertainty surrounding the availability of the required feedstock to meet the expected future demand of Italian industry is an additional concern.

Another consideration relates to the technological lock-in of gas-based solutions and their associated costs for industries. If companies fail to embark on the electrification pathway and continue to use a technology mix based primarily on gas (as in the BAU scenario) and electricity from the grid, the increase in the gas price brought about by the ETS2 will drive up operational costs by 50 percent in the food and beverage sector and 54 percent in the textile sector, compared with the electrification scenario.

A specific static analysis of the above-mentioned sectors shows that although full electrification is technically feasible, high electricity prices remain a major short-term barrier. With electricity costing about five times more than fossil gas (in the absence of carbon prices, as is currently the case for SMEs in Italy), electrification is only attractive once heat pumps achieve a COP above 4.5. Such viability depends largely on operating conditions, with low-temperature systems offering the widest cost-effective range. In larger installations, the ETS can improve the economics of electrification by reducing the electricity-to-gas+CO_2 price ratio – even with these benefits, however, electrification does not become cost competitive at current energy prices in Italy.

6 Case study: Poland[22]

6.1 Sectoral scope

In 2023, industrial final energy consumption in Poland amounted to 160 TWh (Eurostat 2023), accounting for 20 percent of the country's total final energy consumption. CO_2 emissions from manufacturing have remained at similar levels over the past several years, reaching over 60 million tonnes annually and accounting for almost 19 percent of national CO_2 emissions (Statistics Poland 2023). Energy consumption in industry has grown steadily thanks to national economic growth, except in 2020, when industrial production dropped for the first time since 2013 due to the Covid-19 pandemic, and in 2022 and 2023 when it declined for the second time as a result of the energy price crisis. National industry is heavily dependent on fossil fuels, with coal and fossil gas being responsible for 40 percent of industrial final energy consumption. Meanwhile, electricity consumption accounts for 30 percent of total industrial final energy consumption (Figure 27).

Demand for industrial heat varies according to temperature levels and end uses in the respective industry sector. The three biggest sectors with low and medium heat demand in Poland are the paper and paper product, food and beverage and chemical industries, respectively accounting for 11 percent, 13.6 percent and 18.6 percent of final energy consumption in industry between 2013 and 2023 (Eurostat 2023).

Final energy consumption in the paper, food and chemical industries totalled 17.2 TWh, 24.2 TWh and 31.1 TWh respectively in 2023. Solid biomass accounts for the largest proportion of final energy consumption in the paper industry, while fossil fuels – mostly fossil gas and solid biofuels – dominate final energy consumption in the food and chemical sectors (Figure 28).

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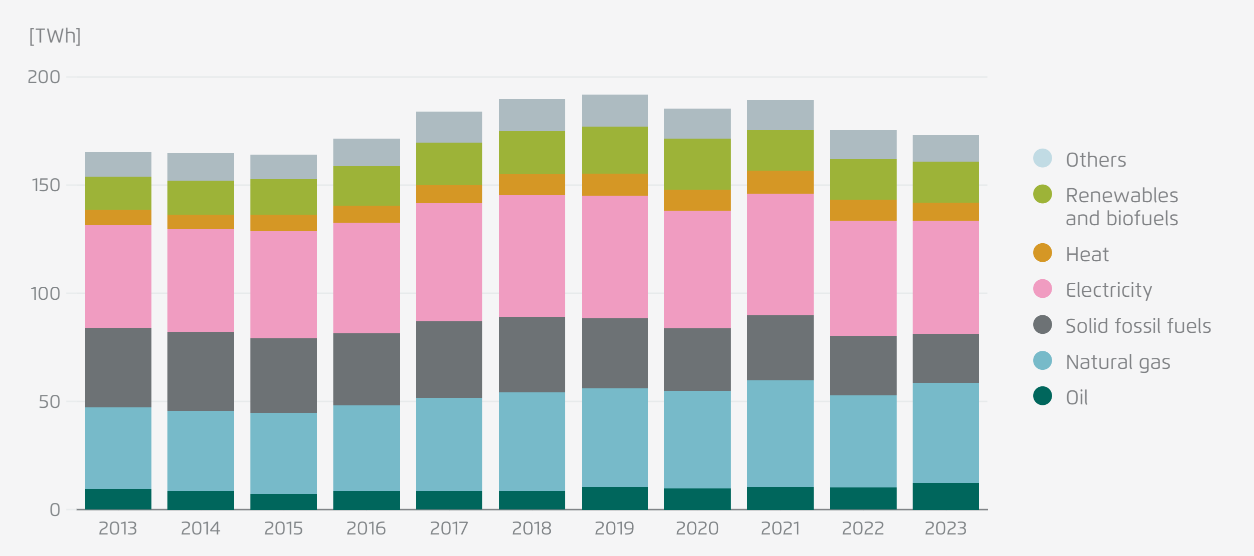
[22] Based on Reform Institute (2025).

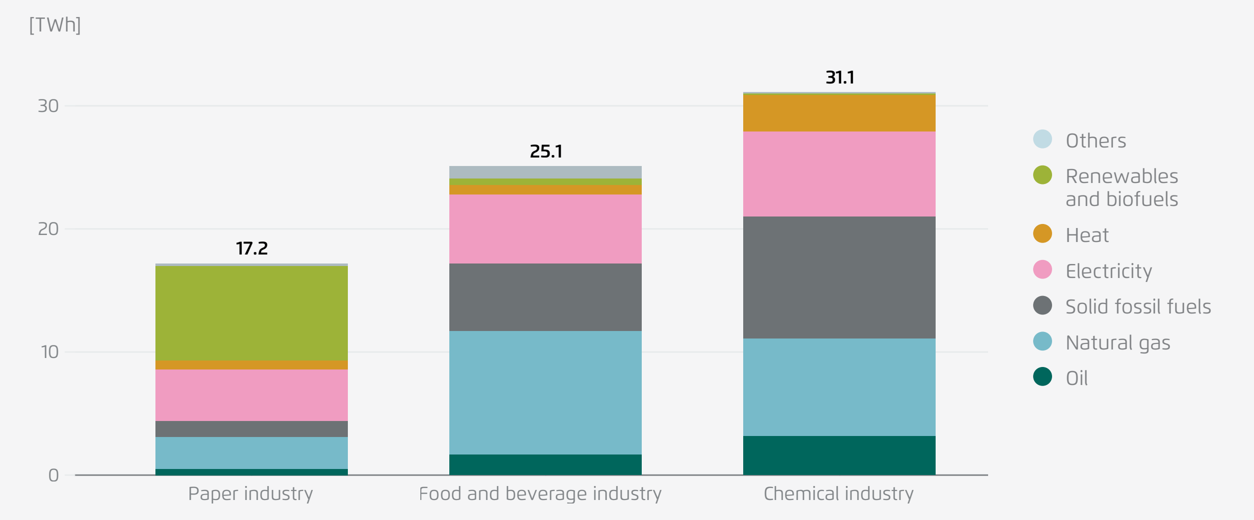
Final energy consumption in industry by fuel in Poland → Fig. 27



Eurostat

Final energy consumption in selected sectors in Poland, 2023

→ Fig. 28



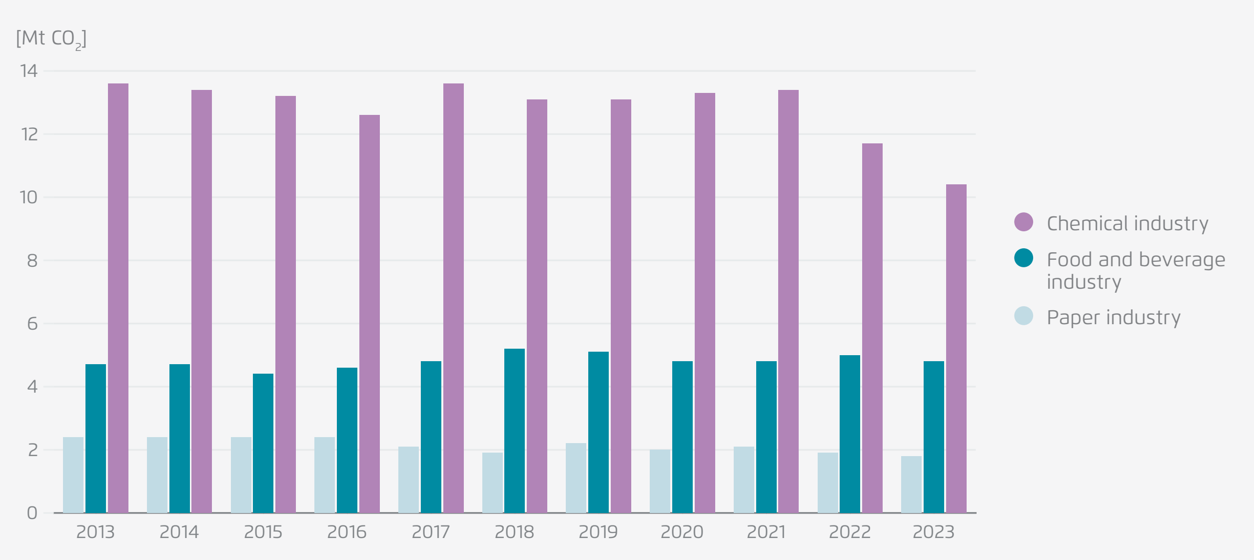
Eurostat

CO_2 emissions from manufacturing show limited variance over the past several years, reaching 60–65 million tonnes annually. CO_2 emissions from the paper industry account for three percent of overall emissions from manufacturing. CO_2 emissions from the food industry are more than twice as high. The chemical industry produces the greatest amount of carbon dioxide and is responsible for 20 percent of industrial emissions (Figure 29). The decreases in CO_2 emissions seen in the chemical industry in 2022 and 2023 came primarily from production cuts.

These sectors were selected not only because of the large amounts of low- and medium-temperature heat they use, but also because of their relevance to the Polish economy. Among the three, the food industry has the greatest impact on the national

CO_2 emissions in selected sectors in Poland

→ Fig. 29



Eurostat

economy, it being the sector with the largest output (approx. 427 billion Polish zloty, PLN) and accounting for 18.9 percent of the entire Polish manufacturing industry's output. The paper and chemical industries have a global output of PLN 79 billion and PLN 60 billion respectively. The food industry also employs the largest number of employees, namely 389,900. The paper and chemical industries employ 63.100 and 107,000 people respectively. Food and beverage exports account for 12 percent of global exports in manufacturing. Exports in the paper and chemical industries represent 2.7 percent and 5.8 percent of manufacturing exports.

A scenario analysis is performed below for specific sections of the above-mentioned sectors, based on the concentration of low- and medium-temperature processes and statistical availabilities.

- → **Food and beverage industry:** manufacture of food products, beverages and tobacco products.
- → **Paper industry**: manufacture of paper and paper products
- → **Chemical industry:** the scope of this study is limited to categories other than "Basic chemicals" in the JRC-IDEES database, namely the "Other chemicals" and "Pharmaceutical products etc." categories. The numbers in the following sections thus relate to part of rather than the entire chemical industry.

6.2 Scenarios

6.2.1 Scenario construction

Three main scenarios are proposed for each sector. The scenarios reflect different technological orientations (Figure 30) but are based on the same assumptions as for energy carriers' cost, CO_2 price and efficiency trajectories (Annex 3, Table 14). The technology mix for each scenario is an input that reflects specific sectoral characteristics but no cost optimisation by actors.

Business as usual (BAU) scenario: This scenario assumes no change in the sectors' heating mix until 2050. The BAU scenario serves as a reference case in which emission savings are only driven by gradual decarbonisation of the electricity and heat grids.

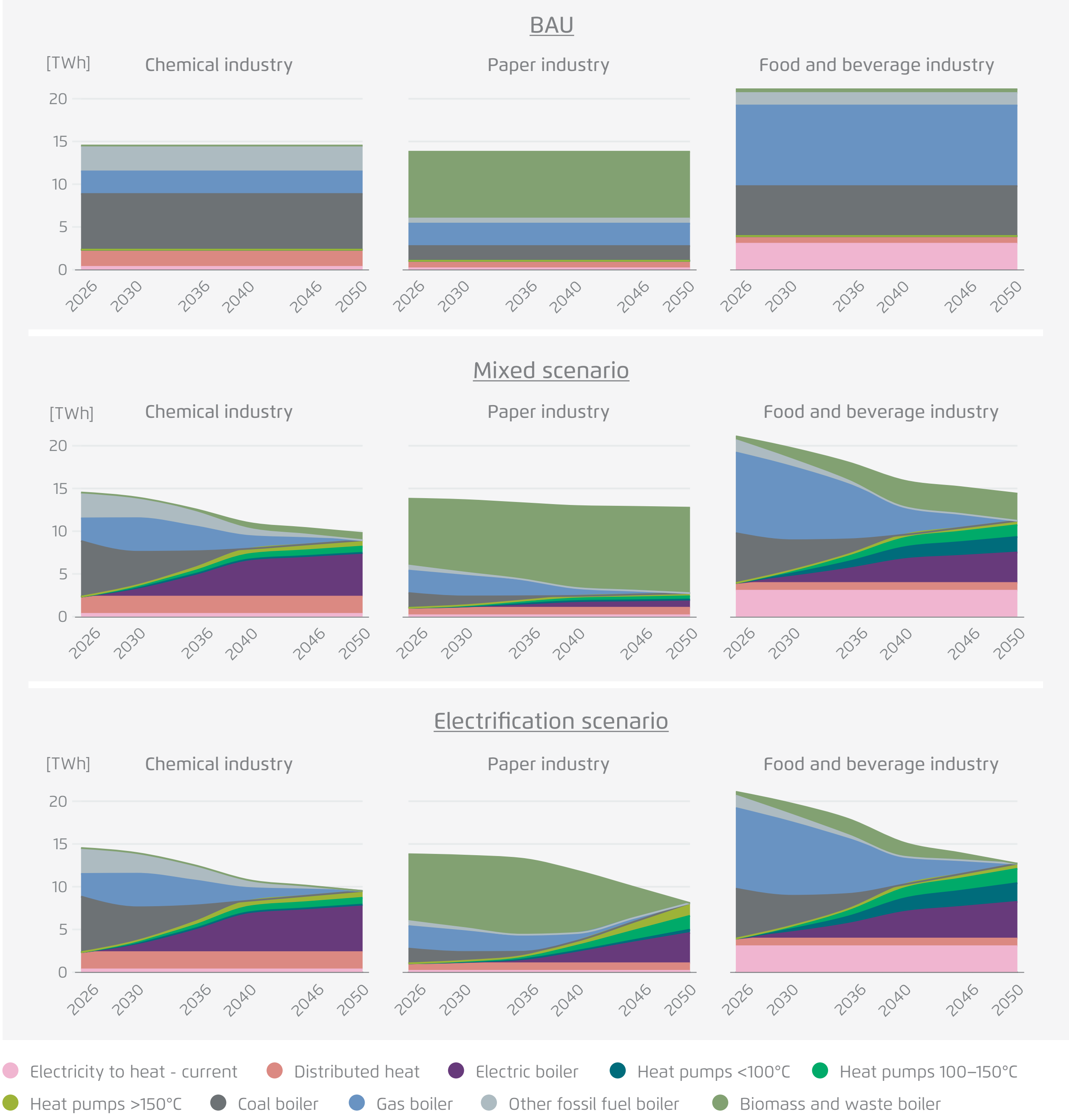
Full electrification scenario: This scenario assumes that all heating appliances will be electrified by 2050, with solid and liquid fossil fuels phased out by 2040. The full electrification scenario is intended to illustrate the costs, emissions and primary energy consumption under a policy context aimed at bringing about full conversion of all heating demand, driven by security and decarbonisation concerns about fossil fuels and concerns about the availability of sustainable biomass.

Mixed net-zero scenario: This scenario achieves net-zero emissions by phasing out coal by 2040 and fossil fuels by 2050. It reveals the costs, emissions and primary energy consumption patterns of a policy context that allows for greater flexibility within a 2050 net-zero target and the continued presence of biomass in the heat mix.

The heating demand in industry is projected to remain at the 2019 level for the foreseeable future. Any gains in efficiency are expected to be offset by growth in output. The efficiency and cost of each technology are also assumed to remain stable given that an increase in efficiency often entails higher capital expenditures. For instance, a heat exchanger offering a smaller temperature difference will have a larger heat exchange surface and thus higher CAPEX cost. The costs of innovative products such as high-temperature heat pumps may fall as new technologies are developed and the production scale is increased; however, such technologies often rely on volatile commodities such as copper or energy-intensive materials such as aluminium and steel, which may become more expensive in the future.

Final energy consumption by technology under different scenarios in selected sectors in Poland

→ Fig. 30



Reform Institute (2025)

6.2.2 Methodology

For each scenario and industry, the useful heat output of each technology is multiplied by its corresponding LCOH to produce estimates of the total costs. These total costs form the basis for assessing the competitiveness of each technology pathway. LCOH figures for each technology, along with the underlying assumptions made about their components, are provided in Annex 3, Table 17.

Changes to energy prices and the energy mix (excluding the BAU scenario) influence costs. To assess these impacts, the projected energy mix is first converted back into final energy carriers, using established efficiency values for each technology (Annex 3, Table 13).

Industrial heat demand is categorised according to five temperature ranges. To simplify modelling, it is assumed that each energy carrier currently meets heat demand proportionally across these temperature ranges. All final energy consumption for heat is converted into useful energy, enabling consistent comparison across technologies and time periods.

The model introduces changes to the heating mix at defined five-year intervals until 2050. In each period, a specified share of the current useful heat demand is reallocated to new energy carriers. In the case of electrification, heat demand is split between heat pumps and electrode boilers. The proportion of heat electrified at each temperature level remains constant across time periods. The ratio of heat pump to electrode boiler depends on heat pump applicability, which declines as temperature requirements increase. Because currently electrified heat is assumed to remain unchanged in all scenarios, its internal composition is not analysed. The phase-out of fossil fuels is progressive but non-uniform, as solid and liquid fossil fuels are eliminated by 2040, whereas fossil gas is not phased out until 2050. In Poland's coal-intensive heat mix, however, gas consumption may rise intermittently as part of the transition.

6.3 Results

6.3.1 Cost assessment

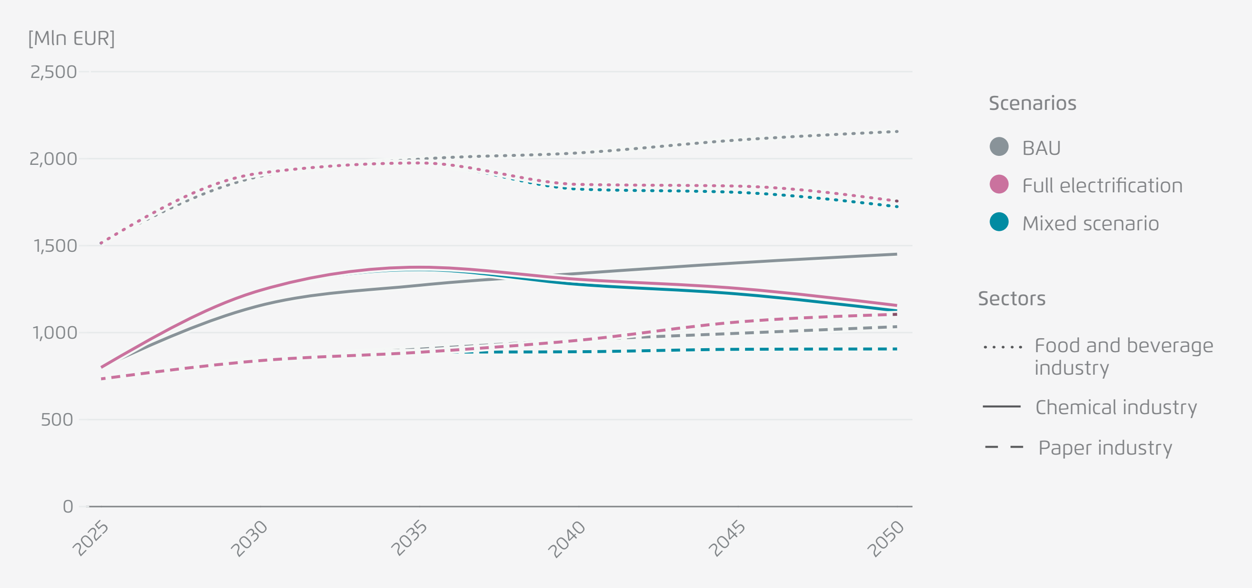
In the food and beverage sector, a comparison of the LCOH shows that despite little initial divergence between scenarios in terms of the costs for the industry, electricity and biomass become much more competitive than fossil fuels after 2035. This is because fossil gas and CO_2 allowances are about to become more expensive, while the price of electricity is set to decline. The difference between BAU and other scenarios increases continuously after 2030 (the year of the energy mix divergence). This includes high CAPEX costs and additional significant financing costs. The mixed net-zero scenario with biomass is slightly cheaper than the full electrification scenario. This difference rises to 89 million euros by the year 2050 (Figure 31).

As is the case with the pulp and paper sector, the LCOH comparison shows that expanding use of biomass is cheaper than maintaining the current heating mix or pursuing total electrification. The mixed net-zero scenario shows that costs rise initially (as in all scenarios); from 2035, however, total costs are reduced thanks to increased reliance on biomass and a declining electricity price. The full electrification scenario reveals a drastic LCOH increase when biomass is about to be replaced with electricity, while the BAU scenario shows a steady increase in the heating price. It is possible that some of the existing newer and more efficient biomass installations can be refurbished and supplied with sustainable biomass until 2050 – certified sustainable biomass is classified as a renewable energy source so burning it does not incur any CO_2 emission costs. Nevertheless, it is crucial to point out that future legislative frameworks may affect the way in which CO_2 emissions from biomass combustion are calculated for ETS1 and ETS2 systems, thus increasing the biomass installation's operational costs. Furthermore, a large increase in biomass-fired boiler capacities would cause a spike in the price of certified sustainable biomass, which in turn would increase the OPEX for such installations (Figure 31).

Finally, the LCOH comparison for the chemical industry shows that using electricity and (for a transitional period) fossil gas to achieve decarbonisation will initially drive costs up but then reduce them compared to the BAU scenario. This is due to the rising costs of fossil gas and CO_2 allowances and the fact that the price of electricity will decline. The difference between BAU and other scenarios increases as the industry advances towards electrification and decarbonisation of the electricity mix. The mixed net-zero scenario with biomass is slightly cheaper than the full electrification scenario (Figure 31).

Cost per scenario in selected sectors, Poland

→ Fig. 31



Agora Industry elaboration of Reform Institute data (2025)

6.3.2 Emission assessment

The BAU scenario involves no changes to the energy mix of the food and beverages industry; however, decarbonisation of Poland's heat and electricity mix will gradually reduce Scope 2 emissions to zero. The other two scenarios also include a gradual phase-out of directly used fossil fuels. The full electrification scenario entails slightly higher emissions than the biomass-based mixed net-zero scenario because new electrified heating incurs Scope 2 emissions from grid electricity that has not yet been fully decarbonised (Figure 32).

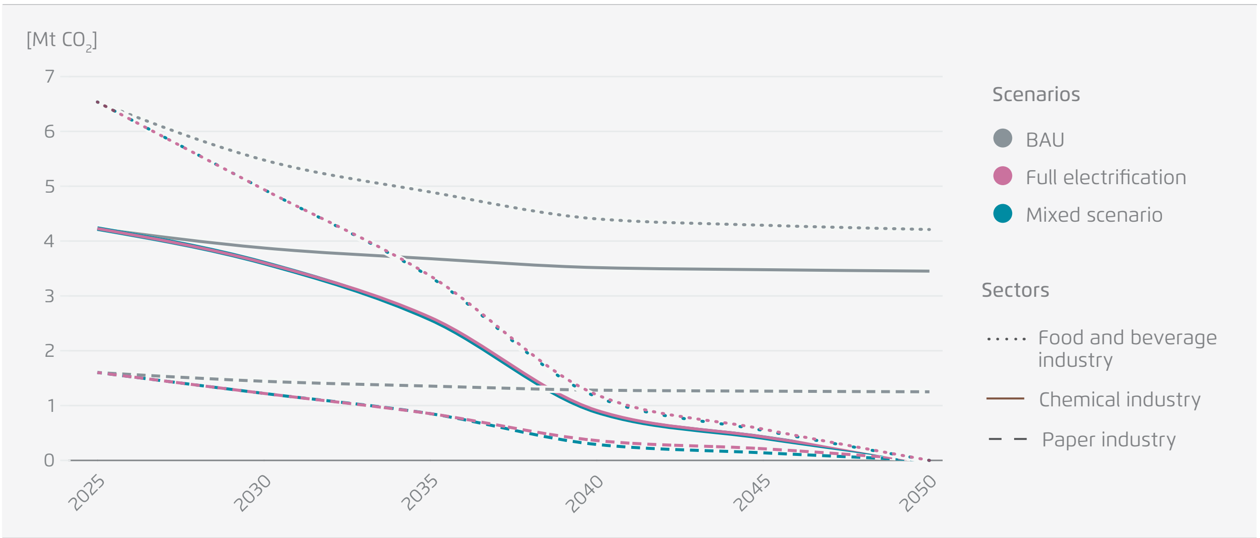
In the paper industry, the BAU scenario involves no changes to the energy mix. The climate impact of the sector's energy mix will be reduced to a minor extent by decarbonisation of Poland's heat and electricity mix. The other two scenarios include a gradual phase-out of directly used fossil fuels. The full electrification scenario entails slightly higher emissions than the biomass-based mixed net-zero scenario because new electrified heating incurs Scope 2 emissions from grid electricity that has not yet been fully decarbonised (Figure 32).

The BAU scenario involves no changes to the energy mix of the chemical industry; however, decarbonisation of Poland's heat and electricity mix will gradually reduce Scope 2 emissions to zero. The other two scenarios also include a gradual phase-out of directly used fossil fuels. The full electrification scenario entails slightly higher emissions than the biomass-based mixed net-zero scenario because new electrified heating incurs Scope 2 emissions from grid electricity that has not yet been fully decarbonised (Figure 32).

Summing up, the proposed decarbonisation pathways tend to follow similar trajectories and, thanks for the most part to the high efficiency of heat pumps, achieve immediate and growing emission savings even given a relatively emissive power mix. Notably, emission reductions can be achieved even if less efficient electrification technologies, such as electric boilers, are deployed, if they initially replace ageing coal-based appliances – and only later reduce the share of gas appliances, once the electricity mix becomes less carbon-intensive (Figure 30). Nevertheless, Poland's relatively high grid emission factor results in higher cumulative CO_2 savings in the mixed net-zero scenario than in the full electrification scenario, though the difference is almost negligible.

CO₂ emissions per scenario in the selected sectors, Poland

→ Fig. 32



Agora Industry elaboration of Reform Institute data (2025)

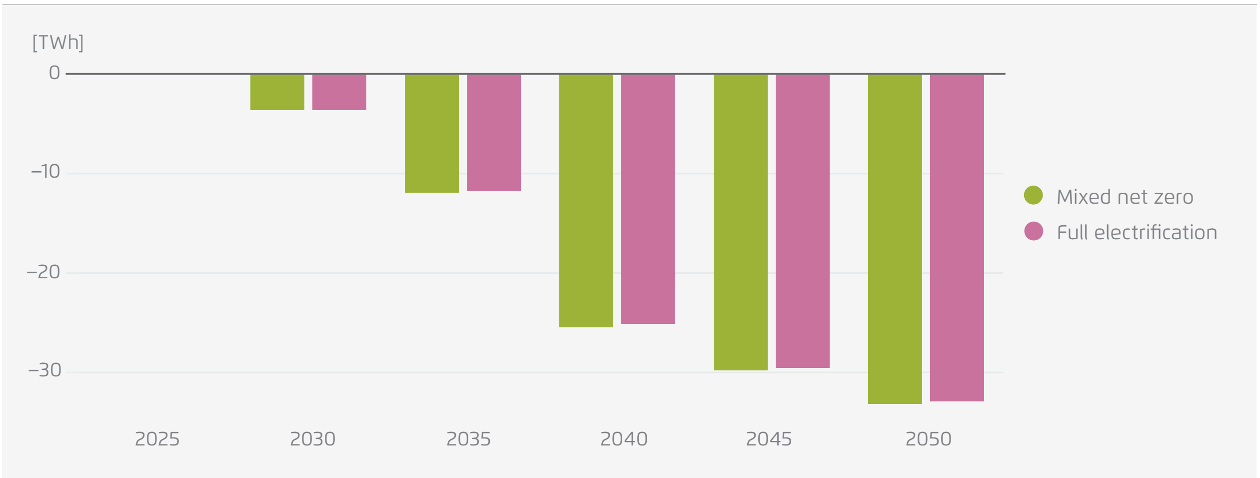
Hence, a more ambitious electrification scenario can reduce the risks associated with large-scale sustainable biomass availability at a very limited emission disadvantage.

6.3.3 Primary energy assessment

Decarbonisation scenarios bring about large primary energy and gas savings, producing substantial energy security benefits compared with the BAU. Notably, full electrification can significantly reduce primary energy consumption, especially in the paper industry, because electric appliances are more efficient than biomass-based systems. Both decarbonisation pathways can save up to 25 TWh of fossil fuel imports (Figure 33)

Avoided fossil energy demand in the full electrification and mixed scenarios in selected industrial sectors in Poland

→ Fig. 33



Agora Industry elaboration of Reform Institute data (2025)

6.4 Main takeaways

This analysis assesses the levelised cost of heat, CO_2 emission and fuel savings across three scenarios in multiple industrial sectors in Poland. Total emissions include not only on-site emissions generated by burning fossil fuels, but also indirect emissions from electricity and district heating consumed on-site. By evaluating these aspects, the study identifies where electrification and alternative fuels could offer both economic and environmental advantages for industrial heat generation.

For each sector it is possible to devise an electrification strategy and fossil fuel phase-out that is competitive across the period in question, provided that the electricity-to-gas price ratio declines steadily as a result of the robust carbon pricing signals and declining power prices assumed by the model (thanks to continued renewable energy capacity deployment). However, the different technological pathways illustrated across the sectors paint an uneven picture. While selected processes in the food and beverage industry can be fully electrified, thus reducing their cumulative costs compared to the current heat mix, the paper industry could be more economically decarbonised with a more eclectic mix including biomass, which is already largely present in the sector's mix, allowing it to remain competitive compared to BAU. The selected processes in the chemical industry show the highest short-term costs with the electrification pathways, with cost parity with BAU only achieved by 2040.

The required process temperature determines whether switching to electric heating technologies is profitable. Low-temperature heat pumps are generally efficient and cost-effective, whereas high-temperature heat pumps entail higher capital and operational costs. In some higher-temperature applications, industries may still rely on electric boilers, which significantly increases both costs and electricity demand. Thus, while electrification offers substantial emission reduction potential, its economic advantage varies across sectors and temperature ranges. While biomass is associated with lower costs, the availability of sustainable biomass remains subject to various constraints and uncertainties.

Among the sectors analysed, the food and beverage industry emerges as the most suitable for electrification. Parts of the chemical industry also show potential for profitable electrification but only given a favourable electricity-to-gas price ratio that is expected after 2040 as a result of increased renewables deployment and carbon pricing. In contrast, the paper industry appears likely to remain competitive if on-site biomass accompanies electrification.

The success of industrial heat electrification will largely depend on whether supportive policy measures are implemented. Differentiated grid tariffs could play a key role by rewarding flexible electricity demand, thereby allowing industries to optimise energy use based on price signals. Likewise, the relative price dynamics between electricity and fossil gas are central to determining the pace of electrification.

7 Outlining the building blocks for resilient, competitive and clean electrification of European industry

The scenario analysis revealed a general advantage of a gradual uptake of electrification technologies in low- and medium-temperature sectors under both business as usual and alternative decarbonisation scenarios in terms of cost, emission reduction and primary energy savings – especially when a cumulative perspective is adopted. As the static analysis showed, however, several barriers still prevent a faster uptake of industrial electrification.

If left unaddressed, these constraints risk locking industry into more emissive technological pathways, perpetuating external fuel dependence and undermining long-term competitiveness. Importantly, none of the identified barriers is structural or insurmountable. Rather, they reflect misaligned policy signals, regulatory inertia, infrastructure bottlenecks and governance gaps that can be addressed through targeted policy interventions at EU and national level. To this extent, the forthcoming Electrification Action Plan constitutes a key opportunity to provide clarity and predictability for industry.

7.1 Enabling industrial electrification in Europe

7.1.1 Technical feasibility

Within the technological and sectoral scope of this study, **technical barriers** to direct electrification do not pose any unsurmountable constraint. The entire low- and medium-temperature heat range can be electrified with existing technologies such as industrial heat pumps and electric boilers. Technological progress can increase the share of heat that can be electrified using heat pumps compared to the range that can only be electrified using electric boilers, without changing the overall electrification potential of the sectors in scope. Accordingly, policy attention should focus not on technology readiness – with the exception of steps to expand the heat range of heat pumps in future, which could be supported by generating clearer and more visible demand for electric heat solutions – but on market conditions and system integration, which is where most obstacles persist.

7.1.2 Correcting incentive structures

The most significant constraint to industrial electrification remains economic. Above all, the electricity-to-gas price ratio is a key determinant in investment decisions. High-temperature heat pumps (80–100 °C) are economically viable only when this ratio approaches three (including CO_2 prices), while very high-temperature heat pumps require ratios below two (Figure 34). In most European countries – such as Germany, Italy and Poland – current price ratios would only support low-temperature heat pumps reaching around 75–80 °C, which account for only a limited share of industrial heat demand and emissions (around five to ten percent).

This challenge highlights the need to structurally realign energy price signals rather than rely on ad hoc support. Required solutions include reducing the relative tax and levy burden on electricity, ensuring predictable and meaningful CO_2 prices and providing transitional support, ideally in the form of derisking, where long-term cost competitiveness is foreseeable but not yet realised.

In addition, even where operating costs are competitive, upfront investment costs – including on-site adaptations, grid connections and integration of heat sources – can deter deployment, particularly for SMEs. While these costs are integrated in the scenario analysis, they are often perceived as prohibitive by small industrial actors facing capital constraints and investment risk. This points to the need for risk-sharing and de-risking mechanisms, as well as access to concessional finance.

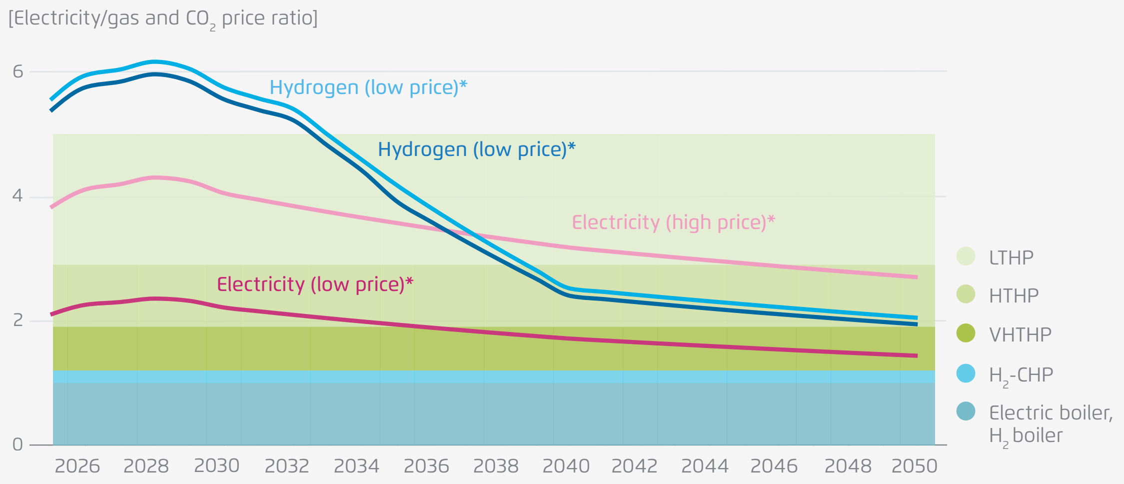
For higher-temperature applications (200–500 °C), electric and electrode boilers offer a technically mature option. However, their cost effectiveness depends largely on their ability to operate flexibly – using hybrid systems or thermal storage to concentrate electricity use during periods of low prices and high renewable availability. This, in turn, requires market and tariff designs that reward rather than penalise flexibility, highlighting the close interactions between economic and regulatory levers.

→ Electrification technologies and the electricity-to-gas price ratio

Energy costs constitute a key determinant when decisions are taken to invest in clean alternatives for process heat generation. Figure 34 provides an overview of the times when clean heat-generation appliances can be run profitably compared to gas-fuelled appliances based on the different electricity and hydrogen-to-gas price ratios derived from the energy price assumptions used in the Germany case study (Chapter 4). Energy and carbon price dynamics are expected to reduce the ratio over time, helping to drive the transition forward. In the background, the efficiency gains of the technologies are indicated to reveal the price ratio at which the technologies become economically viable from an energy cost perspective. Boilers for example require cost parity, while low-temperature heat pumps can be run profitably even at a high electricity-to-gas price ratio. If a lower electricity price is assumed, low-temperature heat pumps (LTHP) and high-temperature heat pumps (HTHP) already offer an advantage over fossil gas. From around 2036, this will also apply to very-high-temperature heat pumps (VHTHP). Even in 2050, however, electrode boilers will not be able to compete with gas on a price basis when operating high full load hours. This would require higher CO_2 prices or lower electricity prices. The hydrogen technologies indicated here do not offer any energy cost advantage over fossil gas.

Energy carrier price comparison and efficiency potential of the technologies

→ Fig. 34



Fraunhofer ISI (2025); *gas price + ETS1; LTHP = Low-temperature heat pump, HTHP = High-temperature heat pump, VHTHP = Very-high-temperature heat pump, CHP = Combined heat and power; Note: Energy carrier and CO_2 price pathways reflect assumptions from Annex 1, Table 5

7.1.3 Infrastructure and system integration

A further challenge lies in the mismatch between the existing energy infrastructure and electrification needs. Industrial sites are typically designed around fossil fuel use, with high gas connection capacities but limited electrical capacity. As a result, electrification often requires electrical connections and transformers to be substantially upgraded, as well as access in some cases to higher-voltage grids. The cost of such upgrades can often exceed the cost of the electrified heat equipment itself.

Moreover, firms depend on external actors such as grid operators and approval authorities, which introduce uncertainty, long lead times and coordination challenges. These factors highlight the need for proactive grid planning and an adequacy assessment that anticipates industrial electrification demand; clearer and more predictable connection timelines are also necessary, as are transparent and fair cost-sharing mechanisms for grid upgrades.

Another system-level challenge concerns the availability of suitable heat sources for heat pumps, such as ambient heat, geothermal energy or industrial waste heat. These sources are not always accessible at the right scale or location, or may be undervalued due to low immediate cost savings, capital barriers or a lack of policy incentives. Addressing this challenge requires waste heat recovery and local resource assessments to be better intregrated into industrial and energy planning.

7.1.4 Addressing organisational and behavioural barriers: managing risk, timing and knowledge gaps

Organisational barriers are hindering the widespread adoption of direct electrification and may continue to do so in the future if left unaddressed. First, replacing fossil with direct-electric installations can physically change the on-site production structure. Examples include integrating heat pumps into processes that previously used one central heat generation installation, or dependency on other actors nearby (e.g. shared heat and material streams or infrastructure). Electrifying existing installations (brownfield investments) can prove challenging – and the technological modification involves risks of longer production stops than the usually yearly refurbishment of existing installations. Greenfield projects offer greater flexibility and easier integration but must be seen as the exception.

A distinct and more binding constraint arises from the long technical and economic lifetimes of fossil-based process heat installations, which commonly extend to several decades. Many assets installed after 2010 are far from the end of their lifetime, leaving firms with little incentive to replace them prematurely. Overcoming this lock-in requires explicit economic incentives for early retirement, repurposing or conversion of fossil heat assets to mitigate stranded-asset risks and unlock faster emission reductions.

At the same time, market and technological uncertainty poses organisational barriers. Misguided expectations about the availability of cheap and abundant alternative fuels, uncertainty about energy and carbon price volatility and doubts about grid reliability can incentivise firms to postpone electrification investments. In this context, indicative electrification targets, clear phase-out signals and technology standards can reduce technological uncertainty, correct misguided expectations and improve coordination across the entire electrification value chains – including power generation, transmission and distribution and appliance manufacturing.

Finally, knowledge and skills gaps – particularly among SMEs – remain a barrier. Though viable electrification options do exist, access to specialised expertise is uneven and the learning and transfer costs related to system design, operation and workforce training can exceed the equipment investment costs. This reinforces the need for technical assistance, skills development and institutional support mechanisms alongside financial and regulatory measures.

7.2 A ten-point plan to electrify European industry

Against this background, and in light of the relevant similarities revealed across the national case studies, there is a rationale for action supporting industrial electrification at European level and mobilising economic, regulatory and governance levers. The forthcoming Electrification Action Plan, which focuses especially on electrification in the timeframe to 2030 to deliver the Clean Industrial Deal's indicative target of a 32 percent electricity share of EU-wide energy demand, should include clear targeting of low- and medium-temperature industrial heat processes. Elements should include the following:

1. **Secure the framework conditions for a predictable pathway to lower the electricity-to-gas price ratio.** The electricity price is a key determinant of the feasibility of electrification – and may vary substantially by end-user group. Rebalancing taxation and levies to reduce the relative cost of electricity is one relevant lever. As gas prices are expected to decline in the coming years, Member States should exploit this window of opportunity to shift taxation from electricity to gas. Nevertheless, taxation rebalancing is ongoing in several jurisdictions and is still unlikely on its own to remedy current gaps in a number of Member States. Carbon pricing will play the largest role role. At a carbon price of EUR 80/t (which is the current ETS1 price), an electricity retail price of up to three times the price of gas is compatible with using heat pumps to electrify temperatures of up to 165 °C. However, as the recent agreement on the ETS2 (applicable to SMEs) introduced a postponement and a limit of EUR 45/t, SMEs will require a maximum electricity price of no more than two times the gas price. The implementation of ETS2 with no further delay remains a cornerstone incentive for the electrification of low- and medium- temperature heat.
2. **Adopt short-term support measures to close the short-term electricity-gas cost gap.** Several national schemes have been introduced to close the cost gap of industrial decarbonisation. For example, Germany has introduced an auction-based carbon contract for difference whose first auction awarded full electrification projects for 28 percent of disbursements and hybrid electrification projects for about 40 percent of disbursements. Similarly, the Netherlands adopted the SDE++ plan with a similar design and purpose. Under the state aid regime of CISAF, however, national schemes are not expected to provide OPEX support – except for industries that are already electro-intensive. In addition, national support could distort the single market and reward electrification in contexts that benefit from greater fiscal scope but do not necessarily present the most competitive contextual conditions for electrification – e.g. cheap and abundant renewable energy supply. Such efforts should therefore ideally be flanked by EU-level instruments that also include temporary and conditional OPEX support. To this extent, the 1 billion euros auction under the Innovation Fund – the first of its kind dedicated entirely to industrial electrification and renewable heating – could serve as a relevant blueprint for the future design of the Industrial Decarbonisation Bank that will be established under the Competitiveness Fund. Key elements must include: i) an auction-based system ensuring efficient allocation; ii) a design that provides sufficient incentives for flexibility and storage, making sure that electrification projects are not conducive to higher cumulative emissions over the asset lifetime in Member States with the least decarbonised mix ; iii) dedicated baskets for electrification, with clear recognition that other decarbonisation options – e.g. hydrogen – do not serve the same purposes and processes and should therefore not be in competition to access support; iv) secure inclusion of SMEs, given the high electrification potential and sector-specific difficulties in accessing EU-level funding; v) prioritise temperature ranges above 80 °C, in order not to concentrate funding in contexts where economic conditions are expected to be favourable to electrification in the near future.
3. **Streamline permitting for industrial electrification projects.** Lengthy and fragmented approval processes often delay projects by 2–5 years and increase capital risk compared to fossil-based

alternatives. Yet the electrification of low- and medium-temperature heat through heat pumps and electric boilers typically brings improvement or no significant change to an industrial site's environmental or safety concept. Targeted action to simplify permitting for industrial electrification projects could help overcome this barrier by building on the Renewable Energy Directive's accelerated permitting provisions, extending them to industrial electrification assets. Key measures could include maximum timelines for permit decisions, one-stop-shop authorities at national level, and "permit-by-rule" schemes for standardised, low-impact technologies. Amendments to the Industrial Emissions Directive could recognise electrification as a Best Available Technology, streamlining approvals. Cohesion Policy funding could support the digitalisation of processes and the buildup of administrative capacity. Environmental assessments could also be harmonised. Where emissions do not increase, project developers could simply notify authorities of energy supply changes without needing to apply for a permit amendment. Where construction law is affected, introducing a notification option in state building codes could ensure alignment and enable developers to make use of accelerated procedures.

4. **Consider a *zero-carbon* standard for new industrial heat appliances, to be gradually phased-in based on temperature and local grid emission factor.** Legacy assets constitute a significant barrier to electrification. To ensure that new investments in low and medium industrial heat generation do not lock in fossil appliances incompatible with the 2040 target, standards for new heat-generating equipment could be established in specific temperature ranges in consultation with industry to account for sectoral specificities, covering first temperatures below 165 °C and gradually expanding to higher temperatures after 2030. All technologies classified as zero carbon are highly efficient, and either use renewable energy directly or will be completely CO_2-free by the year 2035. The standard could cover enhanced waste heat recovery, steam regeneration, heat pumps, electric boilers, solar thermal, concentrated solar thermal, geothermal systems and integrated electrification and waste heat technologies. Medium temperatures between 165 °C and 500 °C could also be covered by the standard before 2030 if the related electricity bidding zone has a low carbon-intensity, or e-boilers are coupled with hybrid or storage solutions, or they are intended to replace coal-fuelled heating appliances. While biomass could also qualify, it is important to note that there are serious availability constraints The Industrial Emissions Directive could constitute the regulatory context to introduce such a standard. While standard can act as a pull factor for investment decision in the enhancement of grids, it is essential that they are accompanied by parallel intervention on supply and permitting bottlenecks (see points 3 and 8).
5. **Guide and monitor the reform electricity grid charges by Member States to enable flexibility and storage.** The design of network charges emerged as a significant hurdle to flexible electrification, preventing the hybrid use of electric boilers and worsening the business case for storage solutions. Electricity grid charges must be reformed to create time-differentiated grid charges so that they incentivise the provision of system-serving consumption flexibility in industry and reduce the privileges for constant electricity consumption. Based on the Affordable Energy Action Plan, guidance on grid fee structure reform was issued in July 2025. This must be accompanied by monitoring of reforms in Member States and complemented by legislative measures in the event that guidance proves insufficient.
6. **Set indicative deployment and phase-out targets.** Demand visibility is an essential condition for investment. Accordingly, the EU should set indicative electrification targets for 2030, 2035 and 2040 on the basis of different heat classes to advance this objective, as well as phase-out dates for the use of fossil gas in low- and medium-temperature heat applications. An electricity share of heat demand of 20–30 percent by 2030 depending on the sector, and of around 50 percent

by 2040[23], is compatible with cost-competitive electrification of low and medium heat demand across several sectors (Fraunhofer ISI (2025, to be published); Annex 5.1, inputs) if the conditions outlined in section 3.1 are met. Notably, indicative targets can be developed in cooperation with industries to highlight respective differences, allowing business to provide demand visibility to both electrification appliance manufacturers and grid operators. This would help minimise the risk of demand-supply mismatches further down the road.

7. **Integrate industrial electrification in the Energy Union revision.** The EU is undergoing a significant legislative overhaul of the Energy Union framework. This includes especially a foreseen revision of the Governance of the Energy Union Regulation. In this context, the reformed package should require Member States to develop dedicated clean industrial heat strategies. These strategies should address infrastructural and resource needs and constraints in their analyses and feed into the Member States' National Energy and Climate Plans (NECPs) for the period 2030–2040. NECPs should provide transparency about the drivers of the electricity-to-gas price ratio and report on measures planned to bring this ratio down to the electrification levels required for the desired decarbonisation pathways. This requirement should be part of the energy security section of the NECPs, given how closely electrification is associated with reduced dependence on imported fuels and the mobilisation of domestic resources for the long-term security and cost-reduction of power systems (Agora Energiewende 2025).
8. **Integrate industrial electrification into grid expansion planning:** The EU should adopt governance provisions requiring national grid operators to take industrial electrification into account when performing adequacy and flexibility assessments and grid planning; provide guidance on maximum timeframes for connecting industries seeking to expand their distribution networks; and help subsidise the minimum share of the cost of connecting to the grid under certain conditions. Efforts should also prioritise concurrent rather than sequential processing of pre-feasibility studies and permitting requests.
9. **Mobilise public-private partnerships for de-risking schemes.** Partnerships between public institutions and private actors – namely utilities and the financial sector – can help reduce risks for investors and bridge the cost gap of electrification. Electrification should be a priority in the "tripartite contracts" announced in the Affordable Energy Action Plan. Dedicated bodies at national level could pool demand among small industrial players for electric appliances such as heat pumps and use this scale to secure cheaper financing from banks, supported by state or European Investment Bank (EIB) guarantees, e.g. via the InvestEU mechanism. Beyond capital investment, schemes could extend to OPEX support in the form of credit guarantees for purchase power agreements (PPA) offtakers to reduce the counterparty risk when long-term contracts are signed with smaller companies. Guarantees should prioritise the SMEs wishing to switch to clean electrification and the emerging strategically important electro-intensive industries involved (e.g. processing and recycling of critical raw materials or battery manufacturing).
10. **Strengthen the EU electrotech manufacturing base by clearly linking the industrial electrification and the broader EU industrial policy agenda.** To address the lack of coordination between technology deployment, manufacturing investment and skills development, the EU should establish an industrial electrification alliance to bring together industrial heat users, equipment manufacturers, utilities, grid operators, financial institutions and public authorities. Building on the experience of existing sectoral alliances, this platform should aim to accelerate the deployment of industrial electrification technologies while strengthening European manufacturing capacity and supply-chain resilience. Such an alliance should support demand aggregation and pipeline development for industrial electrification projects, providing manufacturers of industrial heat pumps, electric boilers, power electronics and related

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[23] Total heat demand includes waste and ambient heat.

components with clearer demand visibility. This would facilitate investment in European production capacity, reduce lead times and improve the availability of maintenance and engineering services – thereby addressing organisational concerns among industrial users regarding reliability and operability. In addition, the alliance should serve as a coordination mechanism linking deployment support with EU industrial policy instruments, including the Net-Zero Industry Act, the Clean Industrial Deal, Horizon Europe, InvestEU and the future Competitiveness Fund. Activities could include identifying bottlenecks along the value chain, supporting standardisation and interoperability, coordinating skills and training initiatives and aligning funding priorities for manufacturing and deployment. In addition, promising and noy-yet mature direct-electrification technologies (e.g., shock-wave heating or plasma torches), or direct electrification technologies showing significant potential for increasing capacity and temperature ranges, should be mainstreamed as a funding priority under different existing funds, including the EU ETS Innovation Fund and Horizon Europe.

8 Annex 1: Technical annex to Chapter 4

8.1 Assumptions

Techno-economic data for selected technologies. → Table 7

Technology	Estimation range	Temperature max. °C	Invest (w/o impl.) [EUR/kW_{th}]	OPEX Fix [EUR/MW_{th}]	Impl. Factor	COP (heat pumps) or efficiency (others)	Energy utilisation factor	Lifetime (years)	Source
LTHP	Low	80	227	4.5	1.2	5		20	Climact (2024)
	Medium		550	11					
	High		875	17.5					Climact (2024)
HTHP	Low	100	100	2	1.5	3.33		20	Climact (2024)
	Medium		700	2.3		3.70			Agora Industrie and FutureCamp (2022)
	High		1.398	4.7		3.33			Climact (2024)
VHTHP	Low	120	350	7	1.5	2.7		20	Heat Pump Centre (2023)
	Medium	150	870	3		2.2			Agora Industrie and FutureCamp (2022)
	High	165	1.023			3.16			Kommunale Wämewende (2024)
EB	Low	500	80	1.6	1.2	0.99		25	Fleiter et al. (2023)
	Medium		175	3.5					Agora Industrie and FutureCamp (2022)
	High		250	5					Agora Industrie and FutureCamp (2022)
NG boiler	Low	> 500	56	2	1	0.91		30	Pezzuto et al. (2019)
	Medium		100			0.93			Grosse et al. (2017)
	High		234	5.9		0.95			Agora Industrie and FutureCamp (2022)
NG CHP	Low	> 500	385	3	1	0.5	0.85	35	Agora Industrie and FutureCamp (2022)
	Medium		515			0.52			Agora Industrie and FutureCamp (2022)
	High		900			0.5			Agora Industrie and FutureCamp (2022)
Biomass boiler	Low	> 500	300	14.5	1	0.75		25	Grosse et al. (2017)
	Medium		391			0.8			Pezzuto et al. (2019)
	High		580			0.88			IRENA (2014)
H_2 boiler	Low	> 500	40,716	5	1	0.97		25	Kommunale Wämewende (2024); Arup Group Ltd (2022)
	Medium		120						Kommunale Wämewende (2024); Arup Group Ltd (2022)
	High		250	12					Kommunale Wämewende (2024); Loes Rutten (2020)
H_2 CHP	Low	> 500	1.256	9	1	0.65	0.97	15	Kommunale Wämewende (2024)
	Medium		1.812	16		0.56	0.92		Kommunale Wämewende (2024)
	High		2.102	20		0.43	0.89		Kommunale Wämewende (2024)
H_2 CCGT	Low	> 500	423,5	3	1	0.5	0.85	35	Agora Industrie and FutureCamp (2022)
	Medium		566,5			0.52			Pezzuto et al. (2019)
	High		990			0.5			Agora Industrie and FutureCamp (2022)

Fraunhofer ISI (2025). Notes: reference year: 2025. For CHP appliances, the primary energy factor indicates the fuel conversion efficiency.

Electricity and carbon price assumptions

→ Table 8

	Unit	2025	2030	2035	2040	2045	2050
Electricity (total price)	EUR/MWh	263.34	261.63	259.93	258.22	256.52	254.86
Electricity (reduced price)	EUR/MWh	123.65	121.95	120.25	118.54	124.16	124.16
Hydrogen (import)	EUR/ MWh_{lhv}	206.6	177.3	147.7	143.7	139.7	135.7
Hydrogen (transition)	EUR/ MWh_{lhv}	326.7	317.0	259.0	174.3	167.0	164.0
Fossil gas / biomass	EUR/MWh	41.9	28.5	30.8	33.2	35.5	37.8
EU-ETS*	EUR/tCO_2	84	132	155	179	194	210
ETS2 / BEHG*	EUR/tCO_2	55	124	151	172	188	200
Electric grid emissions	gCO_2/kWh	300	83	17.9	0.1	0	0

Fraunhofer ISI (*Agora Energiewende). Notes: Total price including all taxes, levies and grid fees. Reduced price includes reduced taxes, levies and grid fees as a basis for industrial consumers. Import: price of imported green hydrogen. Transition: price of hydrogen initially produced locally with increasing import shares over time.

Primary energy factors for the electricity grid, hydrogen supply and fossil gas in Germany over the period under review

→ Table 9

Primary energy factor	2025	2030	2035	2040	2045	2050
Electric grid	2.5	1.5	1.33	1.17	1.1	1.1
Hydrogen supply	3.85	2.31	2.05	1.79	1.69	1.69
Fossil gas	1.2	1.2	1.2	1.2	1.2	1.2
Biomass	1	1	1	1	1	1

Fraunhofer ISI (2025)

8.2 LCOH calculation

$$LCOH = \frac{(\sum CAPEX*AF)*IF^{n-n_0}+(OPEX_{fix}+(COP*P_{Energy}+E*P_{CO2})*FLH)*t}{FLH*t}$$

With:

→ **CAPEX:** capital investment
→ **AF:** annuity factor (depending on interest rate and lifetime)[24]
→ **IF:** innovation factor (reduction in CAPEX over time)
→ **n:** current year
→ **n_0:** start year (2025)
→ **$OPEX_{fix}$:** fixed operational expenditures
→ **COP:** coefficient of performance (efficiency)
→ **P_{Energy}:** price of energy in EUR/MWh
→ **E:** emission factor (fossil or electric grid see Table 5)
→ **P_{CO2}:** price of CO_2 emissions in EUR/t
→ **FLH:** full load hours
→ **t:** lifetime

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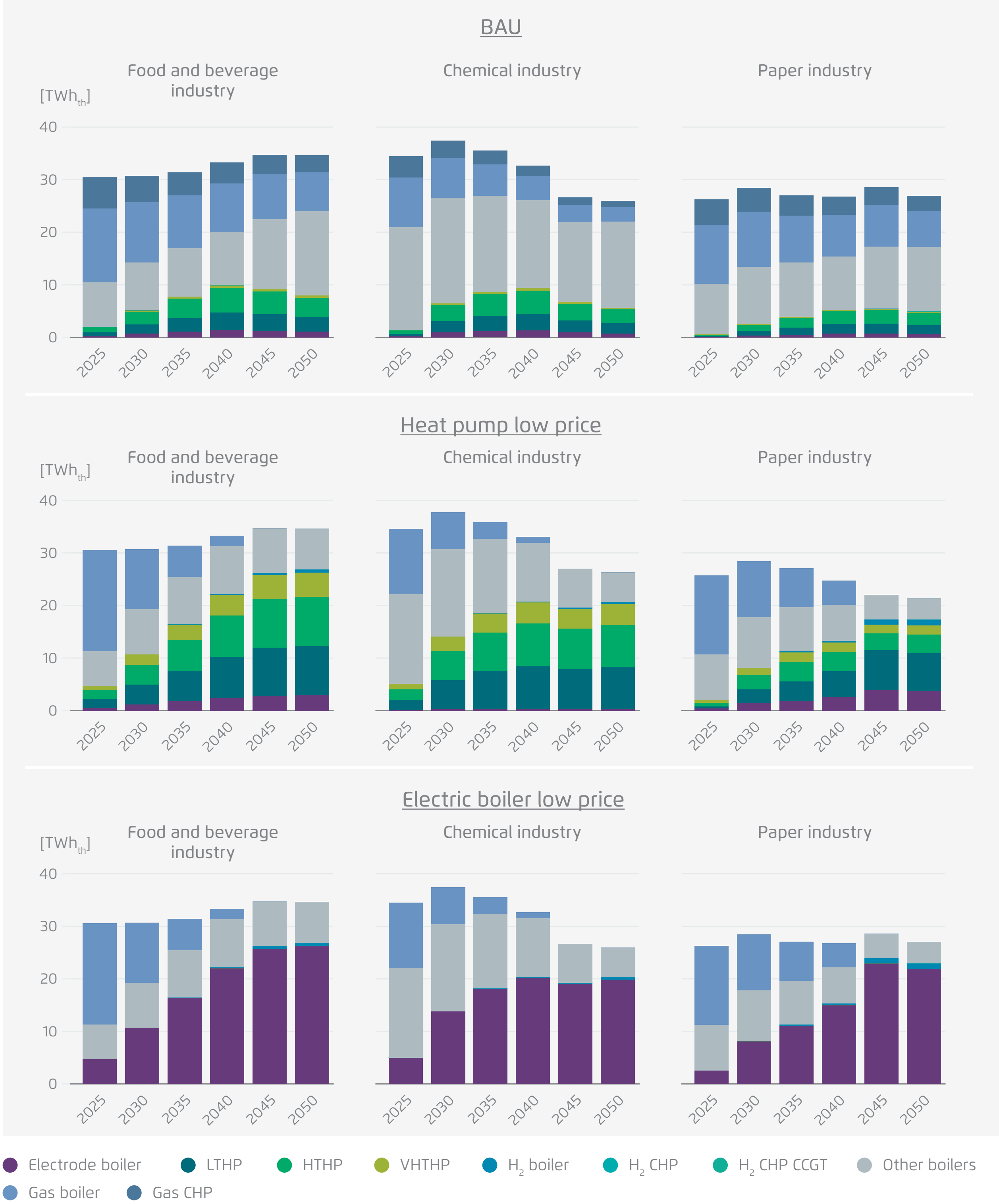
[24] 5% interest rate, 6400 full load hours per year

8.3 Inputs

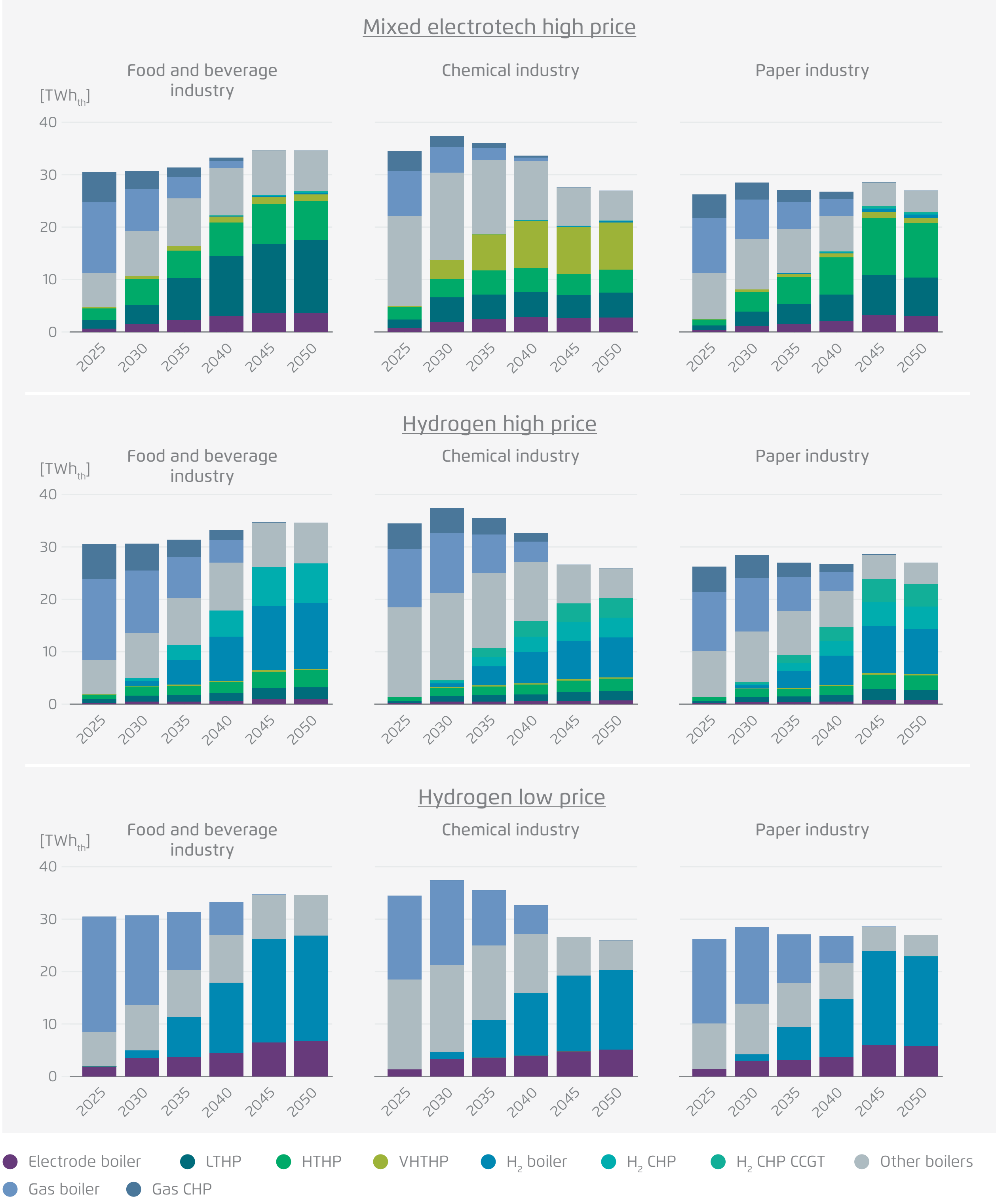
Heat technology mix by scenario and sector in Germany → Fig. 35a



Electrification and hydrogen scenarios: Fleiter et al. (2024); LTHP = Low-temperature heat pump, HTHP = High-temperature heat pump, VHTHP = Very-high-temperature heat pump, CHP = Combined heat and power, CCGT = Combined cycle gas turbine

Heat technology mix by scenario and sector in Germany

→ Fig. 35b



Electrification and hydrogen scenarios: Fleiter et al. (2024); LTHP = Low-temperature heat pump, HTHP = High-temperature heat pump, VHTHP = Very-high-temperature heat pump, CHP = Combined heat and power, CCGT = Combined cycle gas turbine

9 Annex 2: Technical annex to Chapter 5

Techno-economic parameters of the technological options in Italy → Table 10

Technology	Max. efficiency [%] / [COP]	CAPEX 2021 [EUR / kW 2023]	CAPEX 2050 [EUR / kW 2023]	OPEX (exc. energy price) [EUR / MWh 2023]	Operational life [years]
Fuel oil-based technologies					
Steam boiler	97%	63.64	50.1	1.16	25
Hot water boiler	95%	50.14	42.2	1.16	25
Oven	70%	383	324	1.16	30
Fossil gas-based technologies					
Steam boiler	95%	61.7	52.1	1.16	25
Hot water boiler	95%	50.1	42.2	1.16	25
Oven	70%	383	324	1.16	30
Cogeneration plant (CHP)	50%	1567	933	10	15
Biomass-based technologies					
Steam boiler	95%	61.7	52.1	1.16	25
Electricity-based technologies					
Microwave heating	90%	833	749	10	30
Electric heating (Infrared)	96%	572	363	10	30
Electric oven	85%	550	350	10	30
Electric boiler – hot water	99%	137	93	0.58	25
Electric boiler – steam	99%	156.2	96	0.58	25
Heat pump (<80 °C)	COP 4.5	833	730	0.5	20
Heat pump (<150 °C)	COP4	1,220	1,000	0.554	20

ECCO Think Tank (2025)

Energy price assumptions in Italy across different scenarios (EUR/MWh)

→ Table 11

	2021	2025	2030	2035	2040	2045	2050
Electricity (BAU)	68.15405	68.15405	68.15405	68.15405	68.15405	68.15405	68.15405
Electricity (electrification and biomethane scenarios)	68.15405	133.9703	119.1279	104.298	89.48103	74.67743	59.88776
Fossil gas (BAU)	31.066	31.066	31.066	31.066	31.066	31.066	31.066
Fossil gas (electrification and biomethane scenarios)	31.066	51.88	54.9688	59.9085	54.9688	57.36381	47.8408
Fossil gas (market sensitivity analysis)	31.07	51.88	49.97	49.91	39.97	37.36	27.84
Fossil gas + ETS2 – Food and beverage (electrification and biomethane scenarios)	36.80494	59.29648	71.67996	82.58335	84.25748	92.4717	89.9799
Fossil gas + ETS2 – Food and beverage (market sensitivity analysis)	36.8	59.3	66.7	72.6	69.3	72.5	70
Fossil gas + ETS2 – Textile (electrification and biomethane scenarios)	32.50074	53.73412	65.91895	77.61696	80.35059	90.22027	89.9799
Fossil gas + ETS2 – Textile (market sensitivity analysis)	32.5	53.7	60.9	67.6	65.4	70.2	70
Biomethane – outlook	131.88	131.88	134.9688	139.9085	134.9688	137.3638	127.8408
Biomethane (subsidised)	31.066	51.88	54.9688	59.9085	54.9688	57.36381	47.8408

ECCO Think Tank (2025)

Energy carriers’ share of the Italian power mix

→ Table 12

	2021	2025	2030	2040	2050
Fossil gas	52%	46%	42%	28%	–
Fuel oil	6%	6%	5%	3%	–
Coal	5%	5%	–	–	–
Renewables	37%	43%	53%	69%	100%

Piano nazionale integrato per l’energia e il clima (2024)

10 Annex 3: Technical annex to chapter 6

10.1 Assumptions

Energy carriers' share of the Italian power mix → Table 13

Technology	Temperature max °C	Investment cost (EUR/kW_{th})	Fixed OPEX (EUR/MWh_{th})	Discounted capital cost (EUR/MWh_{th})	Share of newly electrified heat	Efficiency (COP for heat pumps)
Coal boiler	>500	190	14.5	2.3	–	89%
Fossil gas boiler	>500	100	2.0	1.2	–	93%
Other fossil fuel boilers	>500	190	2.0	2.3	–	90%
Biomass or waste boiler	>500	580	14.5	7.1	–	84%
Distributed steam	NA	100	2.0	1.2	–	99%
Heat pump 0–100 °C	100	500	2.3	6.1	90%	3.07
Heat pump 100–150 °C	100–150	700	2.3	8.5	80%	2.06
Heat pump 150–200 °C	150–200	870	3	10.6	60%	2.03
Heat pump 200–300 °C	200–300	1300	4	15.9	20%	2.00
Electric boilers, infrared and microwave heaters	600–1000	175	3.5	2.1	Residual range not covered by heat pumps	99%

Reform Institute (2025). Notes: Investment cost has been included in price of heat as annual payment of investment loan, divided by annual heat production measured by utilisation rate. Investment costs and discount rate have been calculated as fixed, therefore discounted capital cost does not change over time.

Energy wholesale prices and carbon price assumptions in Poland

→ Table 14

Price (EUR/MWh$_{th}$)	2030	2035	2040	2045	2050
Coal	11.9	11.9	12.6	13.3	14.4
Fossil gas	42.8	42.8	42.8	44.3	45.4
Other fossil fuels	90.0	100.0	100.0	100.0	100.0
Biomass or waste	18.9	19.2	19.3	19.5	19.7
Distributed steam	24.5	24.6	24.9	25.7	26.5
Electricity	117.3	110.5	92.4	90.0	83.2
CO_2 allowance (EUR/tCO_2)	132	155	179	194	210

Reform based on Poland's National Energy and Climate Plan (2025). Notes: Electricity cost for 2030–50 has been taken from tables of hourly electricity price for four weeks that are representative of four seasons supplied by ARE (Agencja Rynku Energii – Polish Energy Market Agency). To calculate the electricity price, a baseload price has been taken, since many industries have a stable electricity consumption profile or must work on daytime shifts on weekdays. The price of distributed heat has been calculated as the average of the coal, natural gas and biomass prices, since these three energy carriers are set to play the main role in the heating mix in the near future.

Transport and distribution costs and on-site emissivity of selected carriers in Poland

→ Table 15

Energy carrier	Distribution cost	Emissivity on-site (tCO_2/MWh$_{th}$)
Coal	20% of fuel value	0.337
Fossil gas	10 EUR/MWh$_{th}$	0.200
Any other fossil-derived carrier (LPG, fuel oil, refinery gas, etc.)	10% of fuel value	0.250
Biomass or waste	20% of fuel value	0
Distributed steam	20% of energy value	0
Electricity	50 EUR/MWh	0

Reform Institute (2025)

Emissivity of electricity and marketed heat in Poland (kgCO_2/MWh)

→ Table 16

Emissivity (kg CO_2/MWh)	2025	2030	2035	2040	2045	2050
Electricity	685	374	201	57	23	0
Heat	274	149	81	23	9	0

Reform Institute (2025) based on Poland's NECP

10.2 LCOH calculation

For each heat-generation technology, the lifecycle costs per MWh of heat for each 5-year period were calculated. This includes the short-term marginal costs, which allows in theory for fuel switching in the event of dynamic pricing, and the discounted capital cost per technology, which must be paid regardless of use. Useful energy was converted to final energy based on the efficiency or SCOP of heat-generation technologies. The cost of final energy was calculated according to its price in a given year, including transport/distribution costs. Subsequently, on-site CO_2 emission and maintenance costs were added. The total sum is presented in Table 17. The levelised cost of heat includes both operating and discounted capital costs. A table of LCOH for a given year is presented in Table 18:

Operating cost per selected heating source in Poland (EUR/MWh_{th}) → Table 17

Technology	2030	2035	2040	2045	2050
Coal boiler	75.0	82.7	91.7	97.7	104.6
Fossil gas boiler	85.1	89.7	94.5	99.1	103.5
Other fossil-fuelled boiler	145.0	163.0	169.0	172.7	176.7
Biomass or waste boiler	41.6	41.9	42.1	42.4	42.6
Distributed steam	31.8	31.8	32.3	33.2	34.1
Electric resistance heating	126.9	120.1	101.9	99.6	92.9
Heat pump 0–100 °C	42.2	40.0	34.1	33.4	31.2
Heat pump 100–150 °C	61.5	58.2	49.5	48.4	45.2
Heat pump 150–200 °C	63.3	59.9	51.0	49.9	46.6
Heat pump 200–300 °C	65.1	61.7	52.7	51.6	48.3

Reform Institute (2025)

LCOH per heating source in Poland (EUR/MWh_{th})

→ Table 18

Technology	2030	2035	2040	2045	2050
Coal boiler	77.3	85.0	94.1	100.0	106.9
Fossil gas boiler	86.3	90.9	95.7	100.3	104.7
Other fossil-fuelled boiler	147.3	165.3	171.3	175.0	179.0
Biomass or waste boiler	48.6	48.9	49.2	49.5	49.7
Distributed steam	33.0	33.1	33.4	34.4	35.3
Electric resistance heating	129.1	122.2	104.0	101.7	95.0
Heat pump 0–100 °C	48.3	46.1	40.2	39.5	37.3
Heat pump 100–150 °C	70.1	66.8	58.1	57.0	53.8
Heat pump 150–200 °C	73.9	70.5	61.6	60.5	57.3
Heat pump 200–300 °C	81.0	77.6	68.6	67.5	64.1

Reform Institute (2025)

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Publication details

About Agora Industry and Agora Energiewende
Agora Industry and Agora Energiewende develop scientifically sound and politically feasible strategies for a successful pathway to climate neutrality – in Germany, Europe and internationally. The organisations which are part of the Agora Think Tanks work independently of economic and partisan interests. Their only commitment is to climate action.

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Proofreading: Chris Cave
Typesetting: Urs Karcher
Title picture: D3signAllTheThings | iStock

396/02-S-2026/EN
Version 1.2, March 2026