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Decarbonization of European Industry: Modelling and Open Science (DEIMOS)

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Abstract:

The DEIMOS project developed and applied two complementary open-source modeling frameworks, FORECAST-Sites Extended and iSTEDS, together with openly accessible industrial datasets. These resources enable transparent and reproducible analysis of industrial decarbonization pathways across sectors, technologies, and locations. FORECAST-Sites Extended captures site-specific investment decisions, including asset vintages, reinvestment timing, technology costs, and infrastructure access, while iSTEDS assesses industrial electrification and demand-side flexibility. Applied in three case studies, the models highlighted the roles of hydrogen, carbon capture, and electrification in industrial transformation. Together, the models and datasets provide an open-science foundation for analyzing industrial transition and supporting future energy and climate policy.

Karlsruhe Institute of Technology

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Decarbonization of European Industry: Modelling and Open Science (DEIMOS)

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Final report

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Contents

Executive summary

The DEIMOS project investigated how European industry could transition toward climate neutrality and how this transformation may affect future flexibility potentials within the energy system. To support transparent and reproducible research, the project developed and applied two complementary open-source modeling frameworks, FORECAST-Sites Extended and iSTEDS, together with openly accessible industrial datasets.

The three case studies presented in this report show that industrial decarbonization is highly heterogeneous across sectors and locations. The first case study highlights that technology adoption depends not only on technology costs, but also on site-specific factors such as asset vintages, reinvestment timing, and access to supporting infrastructure. Hydrogen emerges as a key decarbonization option for several energy-intensive industries, particularly steel, but its deployment is strongly influenced by the availability of hydrogen transport infrastructure and the competitiveness of alternative production routes. As a result, industrial hydrogen demand is likely to be concentrated in a relatively small number of regions and industrial sites.

The second case study further demonstrates that the role of carbon capture differs substantially across industries. In sectors characterized by unavoidable process emissions, such as cement and lime production, carbon capture is likely to play an important long-term role. In other industries, it is more likely to act as a transitional technology alongside the deployment of alternative low-carbon production processes.

The final case study highlights that industrial electrification not only increases electricity demand but can also create substantial opportunities for demand-side flexibility. Significant flexibility potentials were identified across a range of industrial processes, indicating that industry could play an increasingly important role in supporting future electricity systems with high shares of renewable generation.

Several overarching conclusions emerge from the project. First, there is no single pathway to industrial decarbonization; transition dynamics differ substantially across sectors, technologies, and locations. Second, infrastructure availability, particularly access to hydrogen networks, can be as important as technology costs in determining investment outcomes. Third, investment and technology adoption are strongly influenced by the timing of asset replacement and reinvestment decisions. Finally, industrial transformation, infrastructure development, carbon mitigation strategies, and energy system operation are closely interconnected and should be analyzed jointly. Together, the results demonstrate the value of open-science-based modeling approaches for supporting the analysis of industrial decarbonization pathways and informing future energy and climate policy.

1 Introduction

1.1 Motivation

The European Green Deal and the "Fit for 55" package set the European Union (EU) on a pathway towards achieving climate neutrality by 2050. Several member states have adopted even more ambitious targets, aiming for net-zero greenhouse gas (GHG) emissions by 2045. Realizing these objectives requires a profound transformation of the energy system, driven primarily by an accelerated deployment of renewable energy sources to phase out fossil fuels and reduce emissions. However, fossil fuels continue to dominate final energy consumption across key demand sectors, contributing significantly to CO_2 emissions.

Industry accounts for approximately 20% of total CO_2 emissions in Europe, making it the third-largest emitter after the energy supply sector and the domestic transport sector [1]. Figure 1.1 shows that the bulk of these industrial emissions arises from the combustion of fossil fuels such as coal, liquid fossil fuels (e.g. fuel oil), and natural gas. Natural gas, long considered a transitional fuel in decarbonization pathways, has recently acquired increased geopolitical relevance, highlighting the urgency of reducing dependence on fossil resources [2]. In this context, alternative scenarios that accelerate decarbonization, particularly in the industrial sector, must be explored.

Figure 1.2 illustrates the heterogeneity of European industry with respect to both greenhouse gas emissions and final energy demand. While iron and steel and cement dominate industrial CO_2 emissions, the chemical sector accounts for the largest share of final energy demand. At the same time, sectors such as pulp and paper exhibit comparatively high energy demand but lower emissions, whereas cement shows high emissions despite relatively smaller shares of final energy demand, i.e. due to unavoidable process emissions. In contrast to the power sector, industrial decarbonization pathways are highly heterogeneous and process-specific [4]. Industrial sectors differ substantially with respect to temperature requirements, process emissions, feedstock use, technology lifetimes, and flexibility characteristics [5, 6]. Furthermore, industrial transformation is strongly constrained by long reinvestment cycles, infrastructure dependencies, and regional production structures [7]. Thus, industrial decarbonization cannot be represented through uniform emission mitigation pathways, but instead requires sector- and process-specific modeling approaches.

This raises the question of how industrial decarbonization pathways, technology diffusion, and future flexibility potentials could evolve across European industry under climate neutrality targets. Addressing this question requires high-resolution, sector-specific data that captures the heterogeneity of industrial processes. Yet, obtaining

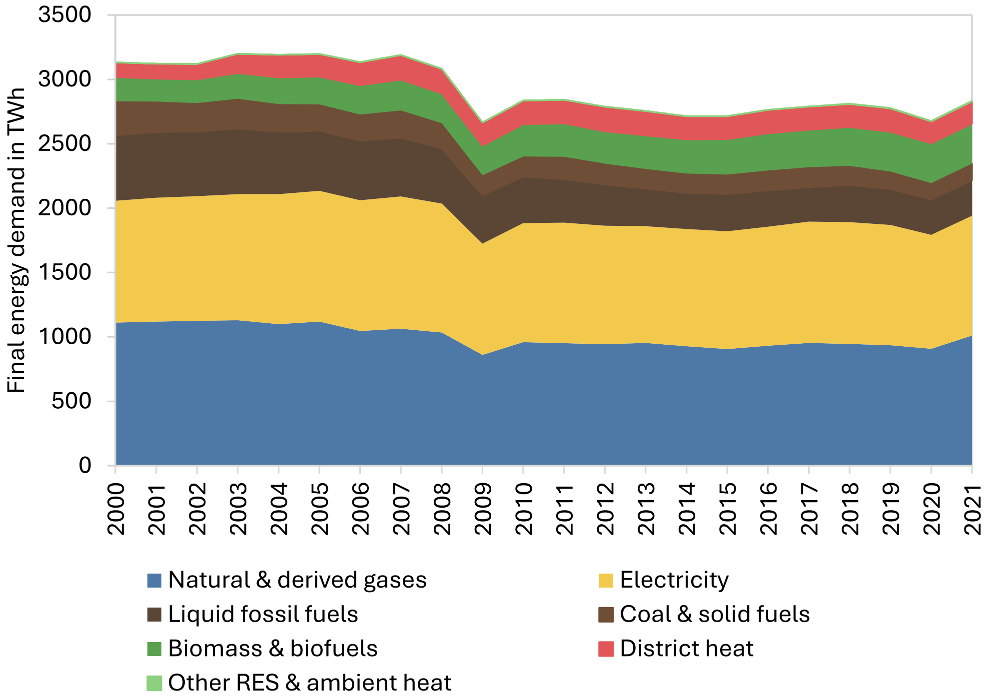

FIGURE 1.1. *Final energy demand of EU27 industry by energy carrier from 2000 to 2021. Data source: JRC-IDEES Database [3]; own aggregation.*

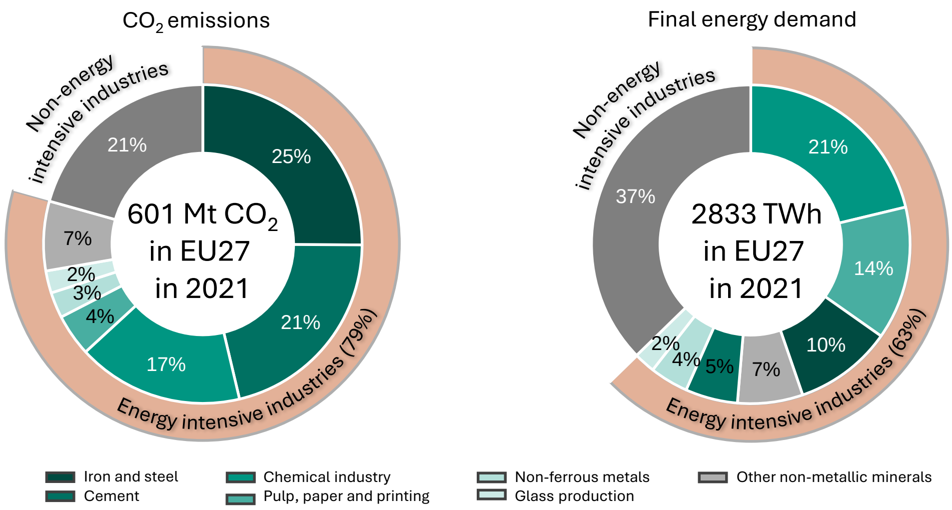

FIGURE 1.2. *EU27 CO_2 emissions and final energy demand by sector in 2021. Data source: JRC-IDEES database [3].*

modeling-relevant data for the industrial sector remains challenging. While several established industrial energy models exist, e.g., FORECAST [5], SmInd [8], they typically provide limited public access to underlying data or model code, restricting transparency and adaptability. A few recent publications have adopted open science approaches, such as the energy system optimization model TEMOA-Europe [9] or the industry-site specific technology diffusion model FORECAST-sites [10].

The present project, DEIMOS, builds on these developments by advancing an open-science-based framework for analyzing long-term industrial transformation pathways in Europe. The project combines openly accessible industrial datasets with site-specific process representations and scenario-based analyses of industrial decarbonization, technology diffusion, and demand-side flexibility. The analysis is guided by the following research questions:

1. How might the technology mix in European industry evolve under different long-term decarbonization pathways?
2. How could industrial electrification affect future flexibility potentials, and which behavioral, organizational, and structural barriers influence their deployment?

To address these questions, the project develops and applies a set of complementary open-source modeling tools and datasets covering industrial technology adoption, carbon capture deployment, hydrogen infrastructure requirements, and industrial demand-side flexibility. By combining site-specific and sector-level perspectives, the project seeks to improve the representation of industrial transformation processes within long-term energy system analysis.

The remainder of the report is organized as follows. Section 1.2 following provides an overview of the main scientific output of the project. Chapter 2 reviews the context, modeling challenges, and positioning of the work in this project as regards industrial decarbonization and demand-side flexibility. Chapter 3 summaries the methodological framework and underlying datasets used to construct the industrial transformation models FORECAST-Sites Extended and iSTEDS. Chapter 4 presents three exemplary case studies on hydrogen demand, carbon-capture technology deployment, and flexibility potentials. Finally, Chapter 5 summarizes the implications of the work and directions for future research.

1.2 Overview of scientific output

Table 1.1 summarizes the principal scientific outputs associated with the DEIMOS project and illustrates the breadth of research activities undertaken. The corresponding references are found in the Appendix. The publications and theses can be grouped into three closely related research areas: site-specific industrial transformation modeling, technology choice and diffusion, and industrial demand-side flexibility. Together, these outputs contributed to the development of open-source modeling frameworks, the expansion of industrial datasets, and the analysis of key decarbonization technologies, including hydrogen-based production routes and carbon capture. In addition, several studies examined the interaction between industrial transformation and energy system operation through

Table 1.1. *Main scientific outputs of the DEIMOS project.*

Citation	Output type	Main contribution	Relation to DEIMOS
Site-specific industrial transformation modelling			
Britto et al. (2026)	Model & dataset	FORECAST-Sites Extended.	Site-specific industrial transformation model.
Britto et al. (2026)	Journal paper	Analysis of hydrogen pathways and infrastructure requirements for the steel and chemical industries.	Sector-specific application of the site-specific industrial transformation framework.
Gröning (2026)	Bachelor thesis	Modeling hydrogen pathways for the European chemical industry.	Updating the site-specific industrial database and improving the methodological depth of the modelling of hydrogen infrastructure development.
Tröndle (2025)	Bachelor thesis	Open-science-based modeling of technology diffusion in energy-intensive industry.	Methodological extension of industrial transformation and diffusion modelling with regard to the iron and steel industry, cement, clinker, and glass production.
Technology choice and diffusion			
Bergler et al. (2026)	Model & dataset	iSTEDS.	Industrial decarbonization simulation model.
Bergler (2026)	Bachelor thesis	Development of a discrete-choice model for carbon-capture technology adoption in European hard-to-abate industries.	Methodological basis for the carbon-capture technology diffusion module of iSTEDS.
Bergler et al. (2026)	Conference paper	Modeling diffusion pathways of carbon capture technologies in hard-to-abate industries.	Investigation of technology diffusion dynamics in industrial decarbonization pathways.
Britto (2026)	Dissertation	Optimal Consumer Adoption of Energy Efficiency.	An economic study of consumer choice and welfare effects of energy-efficiency adoption under uncertainty.
Britto et al. (2022)	Working Paper	Steelmaking technology and energy prices: The case of Germany.	Investigation of short and long-run effects of energy prices on Germany's steel production technologies.
Industrial demand-side flexibility			
Scharnhorst et al. (2024a)	Conference paper	Quantification of future process-specific flexibility potentials in European industry.	Assessment of future industrial flexibility potentials under electrification pathways.
Scharnhorst et al. (2024b)	Journal paper	Empirical investigation of behavioral and structural barriers to industrial demand response participation.	Analysis of organizational and behavioral dimensions of industrial flexibility provision.
Scharnhorst (2026)	Dissertation	Investigation of behavioral and structural drivers of energy demand flexibility.	Broader conceptual and empirical foundation for industrial flexibility analyses within DEIMOS.

assessments of flexibility potentials and the behavioral and organizational factors affecting their deployment. Collectively, the body of work advances the representation of industry in energy system analysis while providing transparent and reproducible tools for future research.

By delivering a fully transparent, high-resolution data and modeling framework, the project provides a robust foundation for evaluating industrial decarbonization strategies. Its open-access dataset and open-source modeling platform will support researchers, policymakers, and system operators in designing effective mitigation measures and integrating industry into future energy system planning, including demand-side flexibility for grid stability.

2 Background

Numerous studies have examined pathways for decarbonizing the European industrial sector under energy systems with high shares of renewable electricity (see chapter 2.1.2). These analyses rely on a broad range of industrial energy models, applying top-down, bottom-up, or hybrid approaches to simulate long-term transformation pathways up to 2050. Briefly, top-down models analyze economy-wide interactions at an aggregated level, bottom-up models focus on detailed technological and process-specific representations, and hybrid models combine both perspectives [8]. However, modeling the industrial sector remains particularly challenging due to its heterogeneity in processes, products, energy carriers, and investment cycles. Existing models therefore differ substantially in their representation of industrial processes, geographic and temporal scope, sectoral resolution, and treatment of technology diffusion and investment behavior.

Many large-scale energy system models represent industrial energy demand only at aggregated sectoral or national levels and therefore lack detailed process- or site-specific representations. Models that do incorporate industrial sites or individual process routes often focus on a limited number of highly energy-intensive sectors and frequently rely on exogenous production assumptions or simplified technology diffusion dynamics. In addition, publicly available industrial datasets remain limited in spatial and technological granularity. Importantly, only few of the reviewed models are currently fully open source while simultaneously publishing detailed industrial site-, process-, and emissions-level datasets. This chapter reviews the context, key modeling challenges, and the positioning of this project as regards industrial decarbonization and demand-side flexibility.

2.1 Industrial decarbonization

2.1.1 Energy demand, emissions & decarbonization pathways

The European industrial sector generated a total of 601 million tonnes of CO_2 emissions in 2021 [3]. As Figure 2.1 shows, Germany is by far the largest emitter, followed by France, Italy, Spain, and Poland. Figure 2.2 presents the aggregated final energy demand by energy-intensive production process: panel (a) shows that the basic chemical industry is one of the largest emitters; panel (b) illustrates the heterogeneity in energy carrier demand by process, showing that despite large shares of natural gas and electricity demand in all industries, the use of other energy carriers can vary strongly. In addition, the composition of industries varies strongly by country. In the following, the industrial energy demand structure is exemplarily detailed for Germany, as it is the country with highest emissions and final energy demand in Europe.

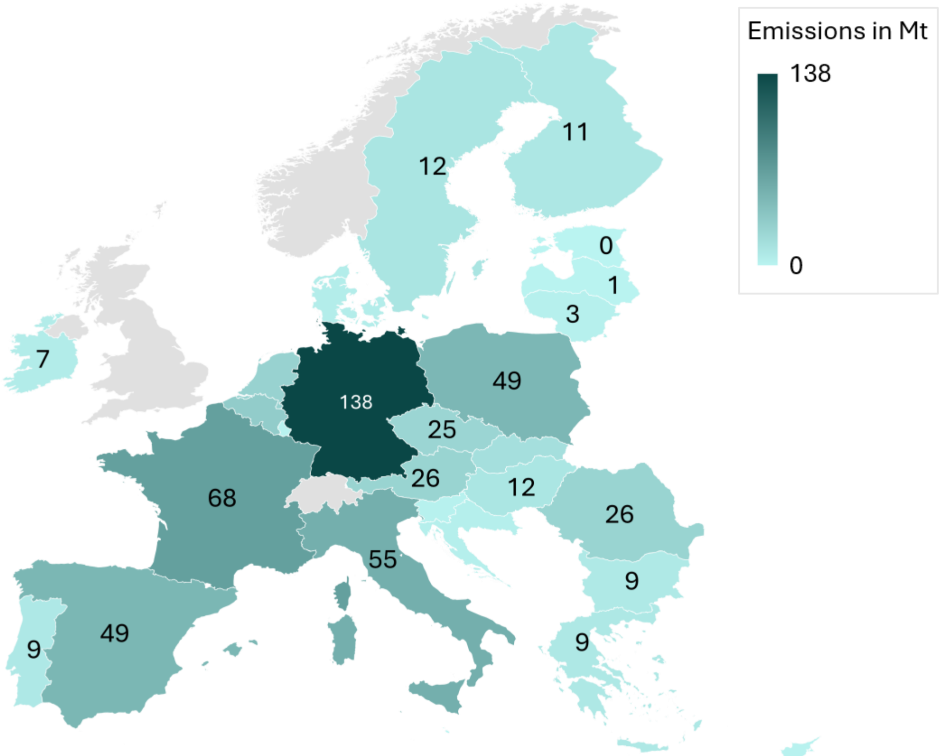

FIGURE 2.1. *Total industrial emissions of EU27 in 2021. Data source: [3].*

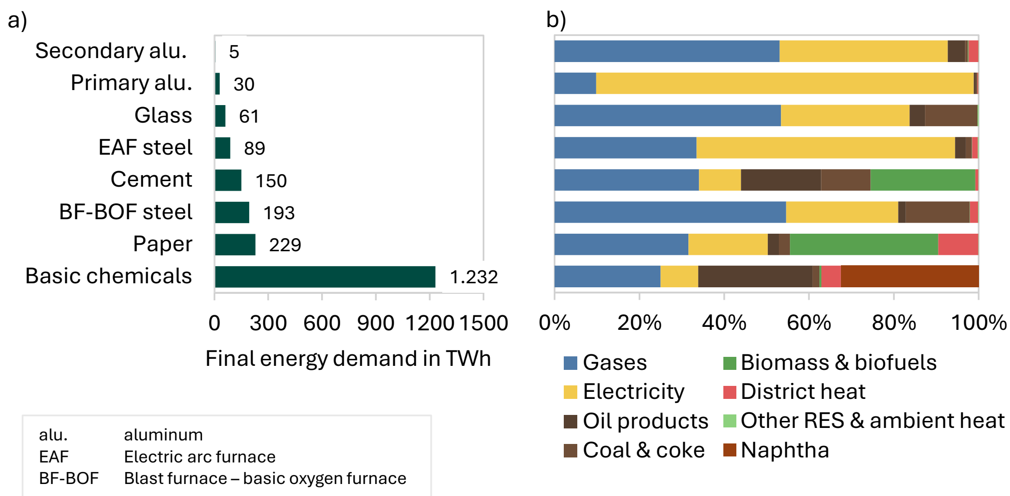

FIGURE 2.2. *Final energy demand of EU27 industry in 2021 by a) energy intensive production processes and b) energy carriers. Sectoral demand is shown in TWh, while shares indicate each sector's contribution to total industrial final energy demand. Data source: [3]; own aggregation.*

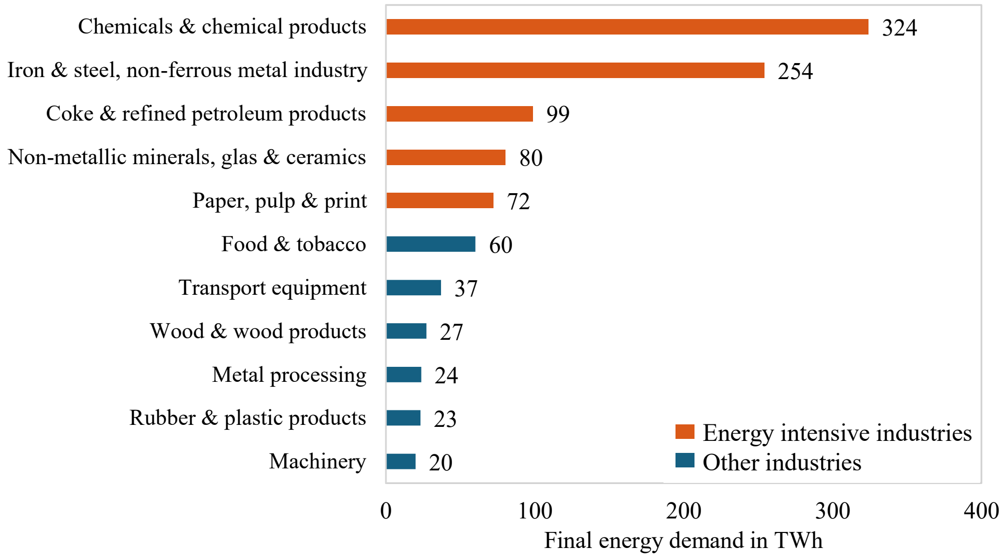

FIGURE 2.3. *Final energy demand of the industry by subsector in Germany 2021, differentiated between energy intensive and other industries. Only industries with > 19 TWh are accounted for in this graphic. Own visualization based on [14].*

The industrial sector in Germany accounted for 656 TWh of final energy demand in 2022, representing a reduction of about 21% compared to 1990 [11, 4]. Over the same period, energy-related greenhouse gas emissions decreased by approximately 48%, driven by significant reductions in the consumption of hard coal (-38%), lignite (-81%), mineral oil (-68%), and more modestly natural gas (-9%) [12, 11]. Biomass use has increased roughly sevenfold since 1990, although it still accounts for only around 5% of industrial final energy demand today [11]. Efficiency improvements and process optimization contributed further to the overall decline in emissions [13].

Industrial energy use in Germany is highly heterogeneous. A distinction is commonly drawn between energy-intensive and less energy-intensive subsectors. Figure 2.3 illustrates that chemicals, iron and steel, non-ferrous metals, coke and petroleum refining, non-metallic minerals (including glass and ceramics), and the paper, pulp, and print industry jointly account for roughly 81% of total industrial final energy demand [14].

Around 60% of industrial greenhouse gas emissions arise from three sectors alone: iron and steel, cement, and chemicals [15]. Industrial process heat is responsible for the majority of emissions (60%), predominantly supplied by natural gas (45%), coal (24%), and, to a lesser extent, district heating (9%), electricity (8%), and biomass (7%) [4, 16]. Figure 2.4 disaggregates process heat demand across subsectors and confirms that natural gas remains the dominant energy carrier, while coal is still concentrated in iron and steel and parts of the non-metallic minerals industry. The largest contributors to process heat demand are iron and steel (27%), basic chemicals (21%), non-metallic minerals (10%), paper and pulp (8%), and food and tobacco (8%) [4]. Electricity plays a comparatively minor role across most subsectors. Only, for the production of non-ferrous metals (43%), mining and quarrying[1] (25%), transport equipment (15%), metal processing (14%), and basic chemicals (11%), higher shares of electricity demand can be noted [4]. Aside from

[1]Subsumed in "Other" in Figure 2.4.

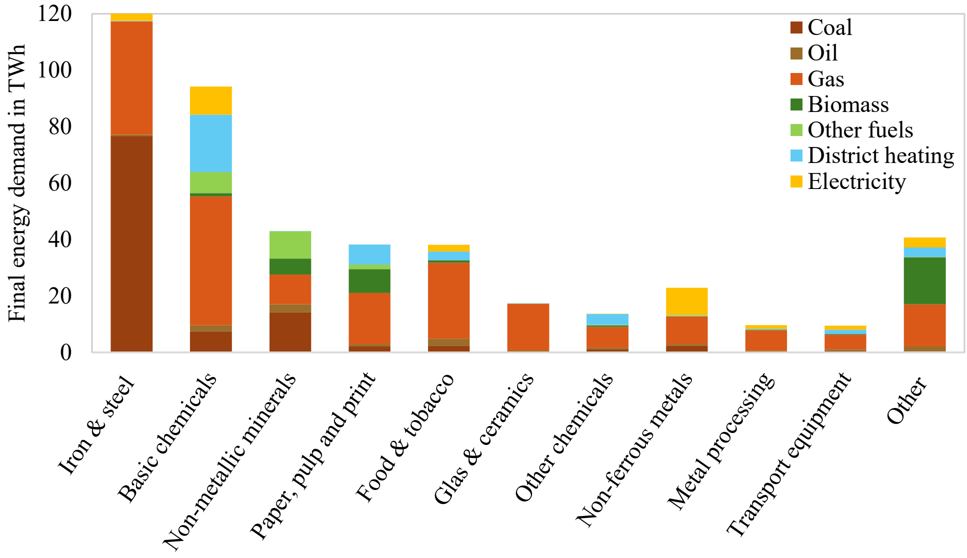

FIGURE 2.4. *Final energy demand for process heat by industry subsector and energy carrier in Germany 2022. Own visualization with data from [4].*

providing process heat, electricity is used primarily for mechanical energy applications such as pumps and compressed air systems [13].

Because process heat supply across nearly all industrial subsectors remains heavily reliant on fossil fuels, electrification technologies are expected to play a central role in future mitigation strategies. Recent assessments conclude that electric process heat technologies, expected to reach market maturity by 2035, could supply up to 90% of today's non-electrified process heat demand, while already available technologies such as industrial heat pumps, electric boilers, and electric arc furnaces could cover more than 60% [4]. This illustrates that a substantial share of fossil-based process heat demand could be decarbonized with technologies that are either commercially available today or expected to be deployable within the next decade.

Looking ahead, scenario projections consistent with the targets of the German Climate Protection Act estimate a decline in industrial final energy demand of 1-24% by 2030 and 8-50% by 2045 relative to 2022 levels [17, 18]. At the same time, electrification is expected to raise industrial electricity consumption by 21-47% by 2030 and to roughly double it by 2045 [15, 18]. By 2045, electricity is projected to supply 65-69% of industrial final energy demand[2], with renewable hydrogen contributing an additional 11% [15, 18]. Electrification of low-temperature process heat (< 500°C) and high-efficiency cross-cutting technologies are expected to drive short-term emission reductions [15]. Industrial heat pumps are projected to reach capacities of 10 GW by 2030 and 35 GW by 2045 [15]. In the iron and steel sector, the shift to hydrogen-based direct reduction is anticipated to account for 39-55% of production in 2045, reducing the reliance on the blast furnace route by about one-third compared to 2019 [18, 17, 13]. Secondary steel production via electric arc furnaces could increase by 50-100% by 2045, supported by improved scrap collection and recycling [18, 17, 13]. Emerging technologies such as iron ore electrolysis are not yet

[2]Of which approximately 17% will be used for low-temperature process heat below 500°C [15].

deployable but may play a role in later global transitions [13]. Additional costs incurred from the production of "green" steel will amount to approximately 1-2% of the vehicle price [15, 13]. In the cement sector, future mitigation is expected to rely on reduced clinker ratios, improved material efficiency, a shift toward timber construction, leading to a reduction of up to 25% in cement demand, and, critically, the deployment of carbon capture and storage to address unavoidable process emissions [15]. The chemical sector is projected to transform its feedstock usage from the utilization of oil to recycled plastics. At the same time, rising imports of green ammonia are expected, while Germany retains domestic production capacity to safeguard fertilizer supply and food production [15].

The literature converges on four principal drivers of industrial decarbonization. First, the decarbonization of process heat through electrification, biomass, renewable gases, district heating, and industrial heat pumps [18, 15, 13]. Second, fundamental process-route changes in energy-intensive industries, including hydrogen-based steelmaking, ammonia, and methanol production, electrification of steam crackers, and substitution of fossil feedstocks with synthetic or biogenic alternatives [18, 15, 13], and implementation of carbon capture and storage technologies in the cement and lime production to account for process emissions [18, 13]. Third, efficiency improvements in cross-cutting technologies such as motors, pumps, and process automation [18]. Finally, enhanced material efficiency and substitution, as well as circular economy measures to reduce the use of energy-intensive primary products [13].

Decarbonizing energy-intensive industrial processes requires a combination of policy measures that both strengthen incentives for emission reductions and mitigate investment risks. The gradual phase-out of free emissions trading system allowances is a key element in reinforcing the carbon price signal faced by firms. At the same time, Climate Protection Contracts (carbon contracts for difference) reduce investment risks for low-carbon industrial processes by compensating firms when the CO_2 price is below mitigation costs and requiring repayment when it exceeds them [19, 20, 18, 15, 13]. Additional measures include the creation of lead markets for green steel [19], the European Carbon Border Adjustment Mechanism, reforms of grid tariffs for flexible loads, targeted subsidies for industrial heat pumps, electricity tax reductions, and strengthened hydrogen and CO_2 infrastructure planning [15].

Finally, the structure of German industry itself may change as the energy transition progresses. Recent research suggests that energy-intensive upstream production stages such as raw iron, steel, ethylene or ammonia, are particularly sensitive to regional differences in renewable energy availability and electricity costs, creating incentives to locate these activities to renewable-rich regions [21, 22]. In contrast, downstream manufacturing stages with higher value added and lower energy intensity are more likely to remain in countries such as Germany, where industrial capabilities, skilled labor, and infrastructure are concentrated [13, 22].

2.1.2 The challenge of modeling industrial transformation

Modeling industrial energy demand and decarbonization pathways poses distinct methodological challenges due to the sector's pronounced heterogeneity, long technology lifetimes, and high capital intensity of production assets [23]. Industrial sectors differ substantially with respect to production processes, products, energy carriers, investment cycles, and flexibility characteristics. Consequently, a wide range of modeling approaches has emerged, ranging from detailed assessments of individual industrial processes and products to aggregated sector-level analyses [8, 7].

Existing industrial energy system models can broadly be distinguished into top-down, bottom-up, and hybrid approaches. Top-down models derive industrial energy demand from macroeconomic indicators and aggregated sectoral relationships, whereas bottom-up models represent technologies, production processes, and efficiency measures in greater technical detail. Hybrid approaches combine both perspectives in order to preserve technological resolution while maintaining consistency with aggregated energy demand developments [8].

Large-scale energy system models typically provide only aggregated sectoral resolution and often represent industrial energy demand at the national level [24, 25]. As a result, process-specific characteristics, industrial site structures, and local infrastructure constraints are frequently not represented explicitly. Technology diffusion is commonly modeled through stock turnover assumptions, exogenous diffusion rates, or aggregated trends over time [26, 27]. Without accounting for plant-specific age structures, reinvestment cycles, and heterogeneous production conditions, only limited insights can be derived regarding the spatial and temporal dynamics of industrial transformation.

More detailed bottom-up and sectoral industry models provide higher technological resolution, but often remain restricted to selected industries or specific transformation pathways. Recent site-specific approaches have focused primarily on energy-intensive sectors such as steel and basic chemicals and frequently investigate prospective hydrogen production and consumption patterns [28, 29]. However, many of these approaches rely on exogenous production forecasts or assume fixed production volumes at the plant level [30, 29]. Furthermore, openly accessible industrial datasets and fully reproducible model implementations remain limited. While transparent and open-source approaches have emerged only recently [10, 9], comprehensive industrial site-, process-, and emissions-level datasets are still scarce across many sectors.

Hybrid modeling approaches provide a promising compromise by combining bottom-up process representations where reliable and sufficiently detailed data are available with top-down representations where data availability remains limited [8]. Such approaches are particularly relevant for assessing future industrial decarbonization pathways and process-specific flexibility potentials at the European scale.

A broad range of industrial energy demand models have been developed at the European level, which we now survey. Prominent examples include energy system optimization models such as TIMES PanEU [31], TEMOA [9], and PRIMES [32], as well as more detailed industry-focused simulation models such as FORECAST [5], WISEE-EDM

TABLE 2.1. *Overview of selected modeling studies scopes*

	Geographic		Temporal		Sectoral	
Model name	Scope	Granularity	Scope	Granularity	Scope	Resolution
Supply chain options [35]	DE, SP, FI	Sites	2050	Ten year steps	Steel	Product
FORECAST-Sites [10, 7]	EU27 + NO, CH, UK	Sites	2050	Annual	Steel, HVC	Product
Location change and vertical integration [36]	NEW	Sites	2050	Five year steps	Steel	Product
IndustryPLAN [37]	EU27 + UK	Country	2050	Annual	Industry	Product Sub-sector
SmInd [8]	EU27 + NO, CH, UK	NUTS3	2050	Annual	Industry	Product Sub-sector
WISEE-EDM [33]	EU27 + UK	Sites	2050	Hourly	Industry	Product Sub-sector
FORECAST [5, 38]	EU27 + UK	Sites	2050	Annual, hourly (e-load)	Industry	Product Sub-sector
TEMOA [9]	OECD Europe	OECD Europe	2050	Five year steps	Industry	Product
JRC-EU-TIMES [39]	EU27 and neighbor-ing countries (36)	Country	2050	Five year steps	Industry	Product Sub-sector
PRIMES [32]	EU27 + UK	Country	2070	Five year steps	Industry	Product Sub-sector

[33], SmInd [34], and recent bottom-up transformation models focusing on hydrogen-based steel and chemical production [10]. These models differ substantially with respect to spatial resolution, process representation, temporal granularity, transparency, and the treatment of technology diffusion.

A prominent example of such an aggregated modelling framework is the PRIMES model, which represents one of the most widely used European energy system models for analysing long-term developments up to 2050 [40]. The model simulates the evolution of the European energy system by incorporating demand and supply interactions, capital and operational expenditures, electrification pathways, and technology vintages, thereby retaining existing assets within the model structure. The model proceeds in five-year time steps and represents industrial demand through sector modules rather than individual production sites [40]. As further discussed by Neuwirth et al. [7], such approaches typically rely on representative stakeholder groups and exogenous assumptions in order to capture the mechanisms of the overall energy system. Consequently, these models remain limited in their spatial resolution, which is usually restricted to the national level, as well as in their temporal resolution and their ability to explicitly represent infrastructure developments such as hydrogen pipeline networks. Similar to PRIMES, IndustryPLAN represents industrial transformation at the country level and does not explicitly account for individual industrial sites or infrastructure constraints. Technology diffusion is driven by exogenous adoption trajectories derived from scenario assumptions rather than endogenous investment decisions [37, 41]. Compared to site-specific approaches, this allows for a comprehensive representation of industrial sectors across Europe, while limiting the analysis of plant-level heterogeneity and spatial infrastructure requirements.

Sektormodell Industrie (SmInd) is a detailed hybrid model that, under the eXtremOS project, published industrial load profiles at NUTS-3 resolution via the FfE Open Data Portal [34, 42]. The dataset differentiates by energy carrier but not by industrial subsector. To date, the eXtremOS dataset represents the most comprehensive data publication for the industrial sector. Building on this example, our project aims to advance openness by not only releasing results but also providing the detailed underlying database—covering industrial sites, technologies, and processes at subsector and NUTS-3/plant-level granularity, alongside the model code itself.

The FORECAST Industry model follows a hybrid approach that combines bottom-up process modeling with top-down application balances [5]. The model includes a broad range of industrial processes and supported the development of a geospatial database of European industrial sites within the sEEnergies project [43]. However, the underlying database itself has only been partially published, such as in the context of the FORECAST-Sites model [10], discussed further below. Furthermore in FORECAST, the technology stock approach is applied, with a statistical distribution leading to gradual replacements over time when installations reach the end of their useful life [26].

One of the most advanced technology- and site-oriented modelling frameworks currently available is the WISEE-EDM model [33]. This framework integrates approximately 800 industrial sites and around 2,600 production units, combining geospatial information with technology-specific parameters such as energy consumption, emission factors, material inputs, and reinvestment cycles. In addition, infrastructure connections, including hydrogen and CO_2 transport networks, are explicitly considered. The framework further allows the aggregation of results from site level to regional, national, and European scales, enabling the identification of industrial hotspots and infrastructure dependencies. However, plant-level information on industrial sites and associated energy demand has not yet been published.

TEMOA-Europe is an open-source energy system optimization model that accounts for energy intensive bottom-up technologies, e.g. in the industry sector, but has limitations in technology diffusion [9]. The model does not dynamically simulate technology adoption based on learning curves or market penetration. Instead, technology deployment constraints are exogenously imposed based on past trends and S-curve adoption models [9]. This means that cost reductions from learning-by-doing or market-driven technology shifts are not naturally incorporated. The model relies on pre-defined demand projections based on GDP and sectoral trends. While some industrial sectors have price-elastic demand (adjusting to gas prices), other sectors do not react to energy costs or technological changes [9].

Building on this methodological progression, the present work follows the site-specific bottom-up modeling approach implemented within the FORECAST-Sites framework developed by [10]. As described by Neuwirth et al. [10], this approach explicitly represents individual industrial sites and plants by integrating a georeferenced industrial plant stock, plant ages, and technology-specific characteristics. This high degree of spatial resolution forms the methodological basis for analyzing technology diffusion pathways and the role of hydrogen infrastructure in the transformation of the European energy intensive industries.

2.1.3 Positioning and contribution

This project addresses several limitations identified in the existing literature on industrial decarbonization and flexibility modelling. Existing industrial energy system models often rely on aggregated sector representations, limited spatial resolution, exogenous technology diffusion assumptions, or non-public industrial datasets. To address these gaps, this project used two industry models to assess technology diffusion for industry decarbonization. The FORECAST-Sites Extended model is an open source model that incorporates spatially resolved industrial site data, process-level techno-economic representations, and technology replacement decisions over time. The model aims to capture how industrial production sites respond to changing energy carrier prices, emissions costs, and investment conditions under long-term decarbonization pathways and was extended in this project methodologically regarding its investment decision logic and a refinement of the hydrogen backbone development and the costs per industry site to connect to the hydrogen pipelines. In addition, a hybrid model, iSTEDS, was used to assess the diffusion of carbon capture in process-emission intensive industries, as well as, for the analysis of future process-specific flexibility potentials. Both models and their input data are published open source to contribute to transparent and reproducible research practices. Together, these contributions aim to strengthen the representation of industry in long-term energy system analysis and improve the linkage between industrial transformation, infrastructure requirements, and future energy system operation.

Table 2.2 compares the two models and highlights their complementary roles within the project. FORECAST-Sites Extended focuses on site-level investment decisions and technology diffusion under heterogeneous local conditions, including differences in asset vintages, production capacities, and access to hydrogen infrastructure. Its high spatial resolution enables the analysis of infrastructure-dependent transition pathways and the identification of site-specific bottlenecks. In contrast, iSTEDS adopts a more aggregated perspective, representing technology deployment at the country and process level based on externally specified technology diffusion scenarios. This allows for the assessment of broader sectoral developments, including the uptake of carbon capture technologies and the emergence of industrial flexibility potentials. Together, the two models provide a consistent framework for analysing industrial transformation from both a bottom-up,

TABLE 2.2. *Comparison of the two main industrial decarbonization models developed in this project.*

Aspect	FORECAST-Sites Extended	iSTEDS
Spatial resolution	Production site	Country
Temporal resolution	Annual	Annual
Main inputs	Energy and technology price scenarios, spatial database of production units, spatial & temporal development of hydrogen pipeline network	Energy and technology price scenarios, gross value added scenarios, technology scenarios (technology readiness level,...)
Main outputs	Annual site-specific technology deployment and associated production & infrastructure costs	Annual country and process/application specific technology deployment
Method	Annual site-specific cost minimization decisions, including the option to shut down production or invest early (dynamic programming)	Annual technology/application specific measure deployment based on exogenous scenarios, logit-based carbon capture technology diffusion

site-specific perspective and a top-down, sector-wide perspective.

2.2 Industrial demand-side flexibility

2.2.1 Flexibility potentials and barriers

This section details industrial demand-side flexibility and is based on material from Scharnhorst [44]. Beyond decarbonizing industrial energy use through efficiency improvements, fuel switching, electrification, and process-route changes, the industrial sector is increasingly expected to provide operational demand-side flexibility. The manufacturing industry is the largest electricity consumer in Germany, accounting for 43% of final electricity demand, compared with 28% in the residential and 25% in the commercial and public services sectors [45]. Demand response is therefore seen as a key flexibility option alongside grid expansion, storage, sector coupling, and flexible generation [46, 47, 48, 49]. Several studies highlight that industrial demand-side measures can provide substantial flexibility and reduce total system costs, particularly in scenarios with high variable renewable penetration [47, 48].

In contrast to the household sector, many industrial firms already operate energy management systems with automated metering, monitoring, and sometimes direct control of machinery [50, 6]. Some energy-intensive companies participate in balancing power markets or interruptible load schemes, yet the bulk of industrial demand response capability remains untapped [51]. Existing studies estimate the technical demand-side management potential of German industry between 2 and 6 GW, depending on the assumed processes and time frames [52, 6, 53]. For comparison, the German annual peak load amounted to about 80 GW in 2021 [54]. To put this estimate into perspective within the broader flexibility landscape, the projected[3] residential flexible capacity could reach

[3]At present, residential flexibility in Germany is largely unrealized, so available estimates necessarily

around 230 GW by 2029, corresponding to more than twice today's national peak demand [56]. While the aggregate industrial flexibility potential appears modest in comparison to the rapidly growing residential flexibility capacity, industrial demand-side flexibility remains highly valuable due to its large unit sizes, high controllability, longer activation durations of several hours, and the fact that many firms already operate advanced automation and metering infrastructure [57, 58]. As a result, industrial demand-side flexibility is particularly relevant for system-wide balancing and congestion management at higher grid levels, whereas residential flexibility is more decentralized and could contribute to relieving local congestion in low-voltage distribution networks [57, 59].

To structure this potential, the literature typically distinguishes technical, economic, accepted and practical demand response potentials [6, 60]. The technical potential comprises all loads that are, in principle, shiftable or curtailable given existing technologies, infrastructure, and process characteristics. The economic potential comprises the share that is profitable under prevailing market conditions. Finally, the accepted potential captures the share of technical flexibility that firms are, in principle, willing to offer ex ante, given risk perceptions, product quality requirements, and organizational constraints, while practical potential reflects the flexibility that is actually provided in operation once these factors interact with market access and incentives [6].

Industrial flexibility arises from a combination of process characteristics, storage options, and production planning choices. Process-related drivers include batch versus continuous operation, availability of intermediate storage, tolerance ranges for temperature and pressure, and opportunities to pre-produce or catch up production. Compared to households, industrial systems often exhibit larger absolute flexible loads[4] and higher degrees of automation, but their flexibility is constrained by tighter quality standards, safety requirements, and complex interdependencies between upstream and downstream processes [52, 61]. The taxonomy of Buhl et al. [61] distinguishes between *organizational* and *technical* industrial demand-side management measures. Organizational measures modify the way production is planned and scheduled without necessarily changing the underlying machinery, whereas technical measures directly intervene in operating parameters, equipment, or energy carriers. Table 2.3 summarizes central organizational flexibility measures identified in the literature.

Technical demand-side flexibility measures intervene more directly in the physical operation of industrial systems. They include, among others, adjustments of process parameters, temporary shutdowns of equipment, use of inherent or dedicated energy storage, and switching between energy carriers. Table 2.4 presents an overview.

The flexibility characteristics of these measures differ markedly. [61] characterize flexibility options using three key indicators: *flexible power* (the load change relative to a baseline), *activation duration* (time between decision and effective load change), and *active duration* (minimum and maximum period for which a measure can be sustained). Organizational measures such as adapting staff break times or working shifts generally involve comparatively long activation durations (hours to days), moderate active durations, and

rely on projected rather than observed capacity [55, 56].

[4]From hundreds of kW to several MW per plant [61].

Table 2.3. *Overview of organizational industrial demand-side flexibility measures. Based on [61].*

Organizational measure	Short description
Adaptation of staff break times	Shifting employee breaks to temporarily reduce or increase electricity use in response to price or grid signals.
Adaptation of working shifts	Aligning shift schedules with periods of low prices or high renewable generation (e.g., nights, weekends, holidays).
Adaptation of order execution sequence	Changing the sequence in which different manufacturing orders are processed, exploiting their differing load profiles.
Capacity planning adjustment	Assigning products to alternative machines with different load and timing characteristics.
Adaptation of production start	Advancing or delaying the start of production runs to better match system conditions or price signals.
Manufacturing order interruption	Temporarily interrupting an ongoing manufacturing order to reduce load for a limited period.
Adaptation of order production sequence	Changing the order of process steps for a specific product across machines with different load profiles.
Adaptation of resource allocation	Selecting machines or lines based on their resource use (e.g., gas vs. electricity) to adapt the electrical load profile.

Table 2.4. *Overview of technical industrial demand-side flexibility measures. Based on [61].*

Technical measure	Short description
Adaptation of operation parameters	Modifying process parameters (e.g., temperature, throughput) within tolerance ranges to change the load profile.
Operation interruption	Temporarily suspending the operation of specific equipment, independent of the manufacturing order being processed.
Adaptation of the operational sequence	Changing the sequence of production tasks within a single machine to alter the temporal load pattern.
Inherent energy storage	Exploiting process-internal inertia (e.g., thermal mass, buffer tanks) to decouple energy input from production output.
Bivalent operation	Switching a system between two energy carriers (e.g., gas vs. electricity) while maintaining product quality.
Energy carrier exchange	Temporarily substituting one energy carrier with another (e.g., combined heat and power plant vs. electric boiler) without altering the process route.
Dedicated energy storage	Charging or discharging dedicated storage (e.g., thermal storage, batteries) to shift electricity draw from the grid.

modest flexible power. Measures such as adapting production start, interrupting manufacturing orders, or reallocating resources can provide higher flexible power with shorter activation times. Technical measures, particularly adaptation of operation parameters and operation interruption, offer substantially higher flexible power (up to several MW in individual plants) and short activation durations, making them suitable for fast-response flexibility products. Measures based on inherent or dedicated storage often provide intermediate flexible power but can be constrained by storage capacity and charging time.

From a system perspective, industrial demand-side flexibility measures can be used across several flexibility applications. [61] match flexibility options and other flexibility technologies (sector coupling, storage, thermal power plants) to three main application categories: integration of excess renewable feed-in, energy-only markets (day-ahead and intraday), and ancillary services (frequency containment and restoration reserves). Sector coupling technologies such as electrolyzers, power-to-heat, or power-to-gas are particularly well suited for integrating excess renewable feed-in due to their long active durations. Large-scale thermal storage and pumped hydro storage likewise support long-duration flexibility. For day-ahead and intraday markets, a broader set of options qualifies: large-scale batteries, thermal storage, combined heat and power units, gas turbines, and many organizational and technical demand-side flexibility measures with sufficient flexible power and activation times on the order of minutes to hours. Ancillary services impose more stringent prequalification requirements regarding response time and minimum bid size [62]. Here, electrolyzers, large-scale batteries, some thermal power units, and a subset of technical demand-side flexibility measures (especially adaptation of operation parameters and energy carrier exchange) can qualify, whereas small-scale devices and many purely organizational measures are typically too slow or too small.

Despite these technical opportunities, the realization of industrial demand-side flexibility potential is constrained by regulatory, economic, and societal factors. The current German regulatory framework has historically provided limited incentives for flexible demand and, in some cases, even penalized it.

Energy-intensive firms can benefit from individually agreed grid fee reduction[5]. At present, around 560 such agreements exist, predominantly in the chemical industry, iron and steel, paper, glass, and food processing sectors, but also partly in data centers and other electricity-intensive activities [63]. In total, these arrangements reduce industrial grid fee payments by approximately 1.42 billion € per year [63]. However, the Federal Network Agency now explicitly assesses the bandload incentive as systemically misaligned under conditions of volatile renewable generation, as it promotes inflexible consumption and can exacerbate congestion and renewable curtailment [63, 64, 65]. The procedure for the determination of the general network charge system for electricity proposes to replace this bandload privilege with a flexibility-oriented incentive scheme, in which future grid fee reductions would be conditional on verified market- or grid-serving load adjustments [63].

In parallel, historically reduced levies and surcharges (e.g., EEG reliefs and electricity

[5] §19(2) StromNEV bandload rule, rewarding constant consumption above 10 GWh/year [63].

tax reductions) have often been tied to high annual electricity consumption and specific efficiency benchmarks, which can create tensions between cost minimization, efficiency improvements, and flexibility provision [65, 66]. The current regulatory reform of industrial grid charges aims to better align network tariffs with grid conditions and congestion patterns, thereby strengthening locational and temporal price signals and indirectly improving incentives for flexible load behavior [63]. At present, clear market-based incentives for industrial demand-side flexibility remain limited, while complex prequalification[6] procedures for participation in balancing markets further constrain the attractiveness of flexibility provision [62, 61, 67].

Societal and organizational aspects play a central role for the realization of industrial demand-side flexibility. The general normative acceptance of the energy transition within German industry is relatively high and flexibility is widely perceived as a potentially important building block of decarbonization strategies. At the same time, the concrete implementation of flexibility measures is strongly embedded in firm-specific organizational cultures, strategic priorities, and monetary efficiency logics [67]. Internal investment decisions remain closely tied to short- to medium-term profitability requirements, while flexibility projects are often characterized by long planning horizons and uncertain returns. Industry actors therefore express strong expectations toward politics to provide stable, transparent, and fair framework conditions. Planning security, transparent price signals, and a coherent regulatory environment are viewed as necessary preconditions for long-term flexibility investments [67]. Furthermore, demand-side flexibility measures that affect staffing patterns, break times, or shift schedules must comply with labor law and be acceptable to employees and works councils [68, 69]. Firms face internal coordination challenges when aligning production planning, maintenance, and energy management objectives. While case studies suggest that demand-side flexibility measures are generally regarded as compatible with the broader goals of the energy transition, their implementation demands careful consideration of workplace conditions, data sharing, and internal communication structures [61].

The economic potential of industrial demand-side flexibility is only a subset of the technical potential once transaction costs, market-access costs, and production constraints are taken into account [60, 6]. Large industrial consumers, such as steel and aluminum mills, constitute the greatest and often also most cost-effective demand-side flexibility potential [70, 6]. Making their potential accessible to the relevant markets can be a great source of low-cost flexibility [47, 48]. At the plant level, for example, Schoepf et al. [71] show for the paper industry that the value of process flexibility is strongly influenced by the relative prices of raw materials and electricity, as well as by product-quality requirements, implying that firms' willingness to invest in flexible technologies and practices hinges on expectations about future energy and input prices. Furthermore, demand-side flexibility competes with other flexibility options such as storage, sector coupling, and flexible generation and will only be realized at scale where market design

[6]The prequalification procedure for industrial demand-side flexibility under the German balancing markets sets strict metering, control, and documentation standards. Meeting these prerequisites may impose a substantial administrative and technical burden, particularly for firms lacking prior experience in market-based flexibility provision [62].

and price signals make it attractive relative to these alternatives [48, 61].

In sum, industrial demand-side flexibility offers significant technical potential, but the gap between technical and practically realized potential remains large. This gap is shaped not only by technological and cost factors but also by regulatory design, organizational routines, and perceptions of risk and complexity within firms. These unresolved issues motivate a closer, empirically grounded examination of barriers and enablers to industrial demand-side flexibility participation, as well as detailed, process-level assessments of future techno-economic flexibility potentials. These topics are taken up in the following subsection as well as in two DEIMOS publications [72, 73].

While the technical and economic potential of industrial demand-side flexibility has been assessed by several studies, substantially less is known about how firms actually make decisions about participating in demand response [6, 74, 67]. More recent studies suggest that participation is shaped not only by financial cost-benefit considerations, but also by cultural, structural, regulatory, and behavioral factors [65, 75, 76, 77]. However, empirical research on industrial demand response barriers remains scarce and fragmented. Prior work often focuses on isolated barrier dimensions, specific subsectors, or regulatory and market perspectives, without systematically capturing how organizational, behavioral, informational, and competence-related barriers interact [68, 65, 61]. This is particularly problematic given the high heterogeneity of industrial consumers with respect to production processes, automation levels, risk exposure, and regulatory environments. Moreover, comprehensive interview-based studies covering multiple sectors and associations across Germany remain rare. This gap motivates the need for an integrated, empirically grounded analysis of industrial demand-side flexibility barriers and enablers. We addressed this need by developing a multidimensional barrier taxonomy and providing a systematic empirical assessment of barrier interrelations based on expert interviews across diverse commercial and industrial actors [72].

Beyond current participation barriers, a second major research gap concerns the future role of industrial demand-side flexibility under deep decarbonization and electrification pathways. Most existing flexibility potential estimates are based on today's production structures and energy carrier mixes, even though industrial processes are expected to undergo profound transformations through electrification, hydrogen use, and process-route changes [6, 52]. As a result, today's flexibility potentials may substantially underestimate the flexibility that could emerge in a future industrial system. To date, no other study has yet addressed future demand-side flexibility potentials at process-level in Europe. We investigate this gap by quantifying the technical future process flexibility potential of energy-intensive industries under ambitious decarbonization scenarios [73].

2.2.2 Positioning and contribution

A major open question in the literature concerns the future role of industrial demand-side flexibility under deep decarbonization and electrification pathways. Most existing flexibility assessments are based on current production structures, process configurations, and energy carrier mixes [6, 52]. However, industrial production is expected to undergo substantial transformations through process electrification, hydrogen integration, and the deployment of new low-carbon production routes. As a result, flexibility potentials derived from today's industrial system may not adequately reflect the flexibility characteristics of future decarbonized industries.

Within DEIMOS, this research gap is addressed through Case Study C, which investigates the future technical flexibility potential of energy-intensive industries under ambitious decarbonization scenarios. Building on detailed process-level representations, the analysis quantifies how industrial electrification and technology substitution may reshape future flexibility provision across European industry. By explicitly linking industrial transformation pathways with process-specific flexibility characteristics, the study contributes a forward-looking perspective that is largely absent from the existing literature.

While future flexibility potentials constitute the primary focus of the DEIMOS work, the realization of these potentials ultimately depends on the willingness and ability of firms to participate in demand response programs. Existing studies suggest that participation decisions are influenced not only by economic incentives but also by organizational, behavioral, informational, and regulatory factors [65, 75, 76, 77]. Nevertheless, empirical evidence on these barriers remains fragmented, often focusing on individual sectors, specific market arrangements, or isolated barrier categories [68, 65, 61].

To complement the process- and system-oriented analysis of future flexibility potentials, a related study conducted during the project developed a multidimensional barrier taxonomy and empirically investigated the interrelations between different participation barriers through expert interviews with industrial and commercial stakeholders across Germany. Although not a central DEIMOS case study, the findings provide valuable context for interpreting future flexibility potentials, highlighting that technical flexibility alone does not guarantee market participation or practical realization. Further information can be found in the publication [72].

Together, these contributions provide both a long-term techno-economic perspective on the evolution of industrial flexibility potentials and an empirical understanding of the organizational and behavioral factors that may influence their deployment in practice.

3 Methodology

3.1 FORECAST-Sites Extended

FORECAST-Sites is a spatially explicit, agent-based simulation model developed by Neuwirth et al. [7] to analyze technological change in energy-intensive industries at high geographical resolution. The model links site-specific industrial data with techno-economic process parameters and represents transformation dynamics at the level of individual production locations. Its empirical basis is a SQLite database containing harmonized information on industrial sites, production units, process technologies, and energy-related characteristics. An overview of the model is shown in Figure 3.1. The model code is freely available.[1] Within the scope of this project, the base model was extensively developed. In particular, as detailed below, the investment logic of the production sites was completely overhauled, as was the calculation of the pipeline-connection costs. The database for the production sites, as well as the input data for the baseline analysis were also extensively updated; this is also described below. The code for the new model is also freely available.[2]

The model follows a bottom-up logic. Rather than representing industrial transformation through aggregated sectoral averages, it simulates decentralized investment decisions under heterogeneous regional and site-specific conditions. This makes it possible to capture differences in the existing capital stock, production technologies, energy prices, and infrastructure access. The spatial resolution is particularly relevant for technologies whose adoption depends on local infrastructure availability, such as hydrogen-based production routes.

FORECAST-Sites Extended is organized into four analytical levels: region, site, production unit, and process. The regional level defines external framework conditions, including energy-carrier prices, taxes, subsidies, energy-carrier availability, and scenario-wide parameters such as the carbon price. Sites correspond to individual geographical production locations and provide the spatial reference for infrastructure-related variables, such as proximity to hydrogen pipelines.

Production units are the core decision-making entities of the model. Each unit represents a production asset at a given site and is characterized by its product, installed process, production volume, and year of last reinvestment. This structure captures both the technological composition and age structure of the existing industrial capital stock. At the process level, the model defines the feasible production routes for each product and assigns process-specific parameters, including capital expenditure, operating expenditure,

[1] https://github.com/fraunhofer-isi/forecast-sites.

[2] https://gitlab.kit.edu/kit/iip/opensource/forecast-sites-ext.

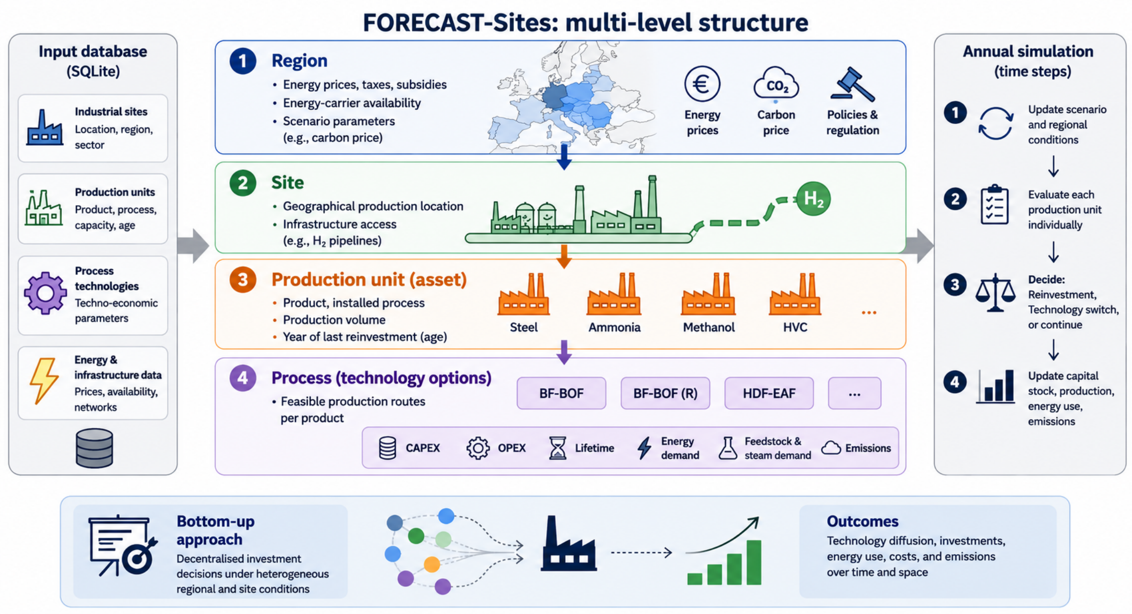

FIGURE 3.1. *Schematic overview of the FORECAST-Sites model; adapted from [7].*

technical lifetime, energy and feedstock demand, steam demand, and process-related emissions.

The simulation proceeds in annual time steps. In each year, regional and scenario conditions are updated, after which each production unit is evaluated with respect to reinvestment, technology switching, and economic feasibility. The model therefore captures both end-of-lifetime reinvestment and premature replacement when alternative processes become economically attractive.

3.1.1 Extensions to the base model

Several core aspects of the original FORECAST-Sites investment logic were substantially extended within this project. In the original model, investment decisions followed a simple replacement rule: once a production unit reached the end of its technical lifetime, it was replaced by the cheapest available production process. The present work introduces two additional decision options that are particularly relevant in the context of industrial decarbonization. First, production units may shut down if reinvestment is no longer economically attractive. Second, units may invest before reaching the end of their technical lifetime if an early technology switch is economically beneficial. In addition, the representation of hydrogen infrastructure costs was refined considerably. Rather than applying a binary connection penalty, the model now explicitly accounts for pipeline distance, connection type, and available capacity when determining site-specific hydrogen connection costs. These methodological extensions are described in detail below.

Browser-based frontend To facilitate the application of FORECAST-Sites Extended and the exploration of its spatially explicit results, a browser-based frontend was developed within the DEIMOS project. The frontend provides an interactive interface for loading model inputs and scenario results, selecting simulation years, filtering industrial products and infrastructure elements, and examining individual production sites. Model outputs can be explored through an interactive map of European production units and hydrogen pipelines, complemented by product-specific summary graphics showing the evolution of production technologies over time. The interface also supports the export of site-level results and map visualizations. Figure 3.2 illustrates the frontend using an exemplary model run.

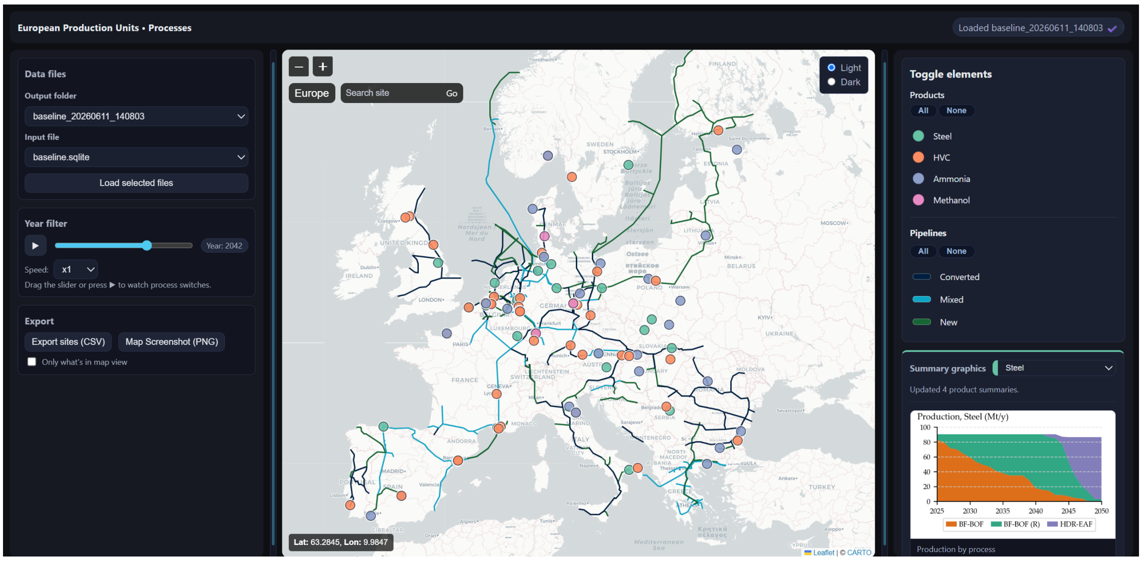

FIGURE 3.2. *Browser-based frontend of FORECAST-Sites Extended. The interface combines an interactive map of European industrial production units and hydrogen infrastructure with scenario controls, technology filters, and product-specific summary graphics.*

Investment and process-choice logic A schematic of the updated investment logic, which is evaluated for each production unit and each simulation year, is shown in Figure 3.3.

Let t denote the current simulation year, p_t the process currently installed in the unit, Q the annual production volume, and y^{last} the year of the last reinvestment. Each process p has a technical lifetime L_p, so that the end-of-life year of the current unit is

$$y^{\text{EOL}} = y^{\text{last}} + L_{p_t} \,. \tag{3.1}$$

If $t \geq y^{\text{EOL}}$, reinvestment or shutdown is mandatory. If $t < y^{\text{EOL}}$, the unit may either continue operating the current process or switch early to a cheaper alternative, subject to an economic threshold.

For each available process $p \in \mathcal{P}_t$, the model computes a discounted replacement-chain cost over a common planning horizon H_t, where

$$H_t = \text{lcm}\{L_p : p \in \mathcal{P}_t\} \,; \tag{3.2}$$

here, $\mathcal{P}_t$ is the set of processes whose energy requirements can be met in year t. The

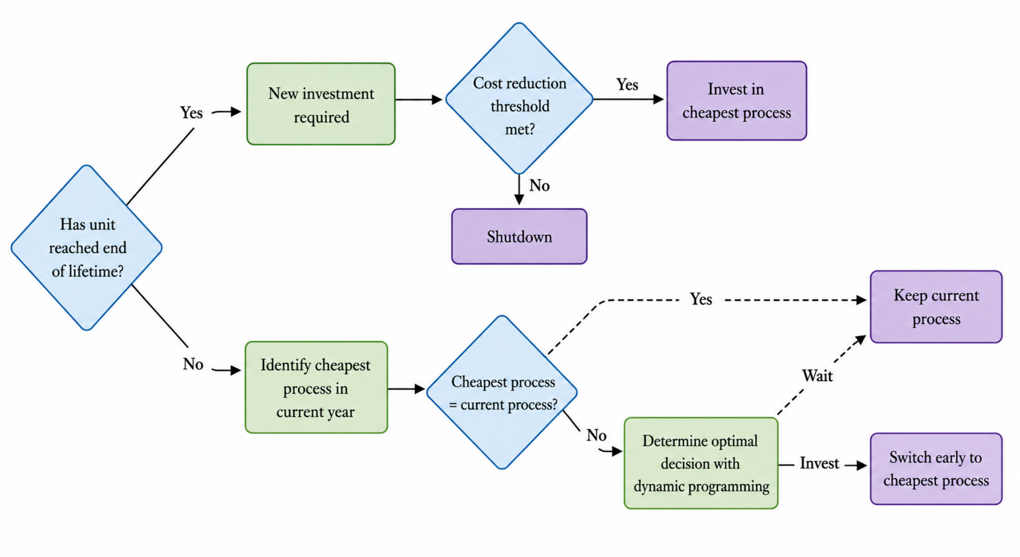

FIGURE 3.3. *Schematic of the process-choice logic.*

replacement-chain cost of investing in process p in year t is given by

$$C_p(t, H_t) = K_p^{\text{pipe}}(t) + \sum_{\substack{\tau=0 \\ \tau \equiv 0 \pmod{L_p}}}^{H_t-1} \frac{Q\, k_p(t+\tau)}{(1+r_p)^\tau} + \sum_{\tau=0}^{H_t-1} \frac{Q\, c_p^{\text{op}}(t+\tau)}{(1+r_p)^\tau}. \tag{3.3}$$

In this expression, $k_p(t)$ is CAPEX per tonne of annual capacity, r_p is the process-specific discount rate, and $K_p^{\text{pipe}}(t)$ is a one-time hydrogen pipeline connection cost, applied only to hydrogen-using processes and omitted once the unit is already connected.

Pipeline costs are computed at site level from the distance to the nearest available hydrogen-compatible pipeline. The model first identifies all pipelines that are available in year t, accounting for commissioning year and assumed build or conversion delays, and selects the closest active pipeline to the site. For realism, pipelines farther than 100 km from the site are deemed unavailable. The one-time connection cost is then

$$K_p^{\text{pipe}}(t) = \begin{cases} f_{m,z}\, d_i(t), & \text{if process } p \text{ uses hydrogen and site } i \text{ is not yet connected,} \\ 0, & \text{if site } i \text{ is already connected,} \\ \infty, & \text{if no suitable pipeline is available.} \end{cases} \tag{3.4}$$

Here, $d_i(t)$ is the great-circle distance in kilometres from site i to the closest available pipeline, $m \in \{\text{H2}, \text{Gas}, \text{Mix}\}$ is the pipeline mode, and $z \in \{\text{small}, \text{medium}, \text{large}\}$ is the required capacity category of the site. The category z is determined from the site's aggregate potential hydrogen demand, while the cost factor $f_{m,z}$ is specified in €/km and differs between new hydrogen pipelines, repurposed gas pipelines, and mixed cases. Once any production unit at a site has connected to hydrogen infrastructure, the connection is treated as sunk and subsequent hydrogen investments at the same site do not incur an additional pipeline connection cost.

Lastly, the annual operating cost per tonne in (3.3) is defined as

$$c_p^{\text{op}}(t) = c_p^{\text{base}}(t) + c_p^{\text{energy}}(t, Q) + \pi_t^{\text{CO}_2}\left(e_p^{\text{proc}} + e_p^{\text{energy}}(t)\right) - s_p(t) + x_p(t)\ , \tag{3.5}$$

where c_p^{base} is non-energy OPEX, c_p^{energy} includes energy, steam and feedstock costs, $\pi_t^{\text{CO}_2}$ is the CO_2 price, e_p^{proc} and e_p^{energy} are process and energy-related emissions intensities, and s_p and x_p denote energy-carrier subsidies and taxes, respectively. Consequently, the cheapest available process in year t is given by

$$p_t^* = \arg\min_{p \in \mathcal{P}_t} C_p(t, H_t)\ . \tag{3.6}$$

If the unit has not yet reached end of life and the current process is already cost-minimising, $p_t^* = p_t$, no early switch is made. Otherwise, the model evaluates whether switching immediately is preferable to waiting. Early retirement of the current process incurs a stranded-capital term:

$$S_t = \begin{cases} Q\, k_{p_t}(y^{\text{last}}) \dfrac{y^{\text{EOL}} - t}{L_{p_t}}, & t < y^{\text{EOL}}, \\ 0, & t \geq y^{\text{EOL}}\ . \end{cases} \tag{3.7}$$

The immediate-investment value is therefore given by

$$I_t = C_{p_t^*}(t, H_t) + S_t\ . \tag{3.8}$$

On the other hand, the value of waiting is computed recursively by dynamic programming. Let V_u be the minimum discounted cost from year u onward, conditional on retaining the current process up to year u. The terminal year is $T = y^{\text{EOL}}$, with terminal condition

$$V_T = C_{p_T^*}(T, H_T)\ . \tag{3.9}$$

For years $u = T-1, \dots, t+1$, the model compares the value of switching in year u, namely I_u, with the value of waiting one additional year,

$$W_u = Q\, c_{p_t}^{\text{op}}(u) + \frac{V_{u+1}}{1 + r_{p_t}}\ . \tag{3.10}$$

The Bellman recursion is defined as

$$V_u = \begin{cases} I_u, & \dfrac{I_u}{W_u} < 1 - \theta\ , \\ W_u, & \dfrac{I_u}{W_u} \geq 1 - \theta\ . \end{cases} \tag{3.11}$$

where $0 < \theta < 1$ denotes the required relative cost reduction for premature replacement. Early switching is therefore allowed only if immediate investment reduces discounted costs by at least θ relative to waiting. Equivalently, the ratio of immediate-investment costs to waiting costs must fall below $1 - \theta$. The threshold prevents marginal cost differences from triggering unrealistically frequent premature technology changes and can be interpreted as a hurdle rate that an investment must clear. The dynamic program terminates by computing the decision in the current year,

$$W_t = Q\, c^{\text{op}}_{p_t}(t) + \frac{V_{t+1}}{1 + r_{p_t}}\ , \tag{3.12}$$

and the unit switches early if

$$\frac{I_t}{W_t} < 1 - \theta\ . \tag{3.13}$$

If this condition is not satisfied, the unit keeps its current process for at least one more year.

At end of life, the cheapest available replacement process is adopted only if it satisfies a minimum cost-reduction requirement relative to the current process. The shutdown hurdle rate $0 < \vartheta < 1$ defines this requirement. If the relative cost advantage of the cheapest replacement process is smaller than ϑ, the available alternatives are considered insufficiently competitive and the production unit is shut down. Economically, ϑ represents competitive pressure at the point of reinvestment and prevents continued operation when replacement would not yield a sufficiently strong reduction in production costs. After a successful investment, the unit state is updated such that $p_{t+1} = p_t^*$ and $y^{\text{last}} = t$.

Hurdle-rate assumptions In the baseline configuration, both hurdle-rate parameters are set to 5%, i.e., $\theta = \vartheta = 0.05$. For premature replacement, this implies that an immediate technology switch is undertaken only if its discounted cost is at least 5% lower than the cost of waiting, corresponding to $I_t/W_t < 0.95$. At the end of an asset's lifetime, the shutdown hurdle applies an analogous minimum cost-reduction requirement to the cheapest available replacement process. These baseline values represent mild competitive pressure and prevent marginal cost differences from triggering unrealistically frequent technology changes or reinvestment decisions. Both parameters are configurable model inputs and can be changed without modifying the underlying investment logic.

Among the sensitivity analyses conducted, an additional scenario examines stronger competitive pressure by increasing the shutdown hurdle rate ϑ from 5% to 10%, while retaining all other model assumptions. The higher value represents an environment in which firms require a stronger economic case to justify reinvestment and continued production. It may reflect more intense international competition, tighter financing conditions, greater uncertainty regarding future demand, or stronger pressure to reduce production costs.

3.1.2 Industrial-site & hydrogen-network data

Steel and chemicals For primary steel, site-level information was compiled from open industrial plant inventories and sectoral statistics. The main data source is the open-source Global Iron and Steel Tracker, which provides plant-level information on steel production sites, including location, operating status, production route, production capacity, and technology type [78]. The raw data were restricted to active production sites in the European study region and harmonised by standardising plant names, technology labels, capacity units, and country identifiers. Each production unit was assigned to a site and process route, allowing multi-unit industrial complexes to be represented consistently within the model. The resulting primary steel dataset contains 44 blast furnace production units. These data were complemented with European steel-sector statistics and energy-system databases, including EUROFER and JRC-IDEES, to validate the resulting aggregate capacity estimates [79, 3].

For chemicals, the primary data source is the Global Chemicals Inventory (GCI), which provides plant-level information on European production sites for high-value chemicals (HVCs), ammonia, and methanol [80]. The database reports plant locations, products, and feedstocks, but does not include production capacities, plant ages, or years of last modernisation. These variables were therefore supplemented using the site-level database developed by Neuwirth et al. [29]. The chemical site data were linked to the supplementary site database using geographic coordinates. The spatial matching procedure identified 56 common chemical sites, corresponding to 83 production units. To ensure consistency with the original FORECAST-Sites framework, the resulting plant counts follow the production-unit assumptions in Neuwirth et al. [10], yielding 53 HVC plants, 38 ammonia plants, and 9 methanol plants. For unmatched chemical sites, production capacities were reconstructed from publicly available company information and project reports. Where no such information was available, capacities were estimated from EU ETS emissions data using process-specific emission factors:

$$Q_u = \frac{\mathrm{CO}_{2,\mathrm{total}}}{EF}, \tag{3.14}$$

where Q_u denotes production volume, $\mathrm{CO}_{2,\mathrm{total}}$ site-level CO_2 emissions, and EF the process-specific emission factor.

Generic industrial site identification using the E-PRTR and EU ETS Emission databases

While dedicated open-science databases are available for selected industrial sectors such as steel and chemicals, comparable datasets do not exist for many other energy-intensive industries. To facilitate the future extension of the modelling framework to additional sectors, a generic methodology was developed to identify industrial production sites using publicly available emissions databases. The approach combines information from the European Pollutant Release and Transfer Register (E-PRTR) and the European Union Emissions Trading System (EU ETS), both of which provide legally verified emissions data for industrial installations across Europe.

The E-PRTR is a publicly accessible European register that documents pollutant releases and waste transfers from industrial facilities exceeding defined reporting thresholds [81]. In addition to annual emissions, the database provides information on facility operators, addresses, industrial activities, and geographical coordinates. However, emissions are reported at the site level and are generally limited to larger industrial emitters, resulting in incomplete coverage of smaller facilities [81, 82].

The EU ETS complements the E-PRTR by providing verified annual greenhouse gas emissions for a broader range of industrial installations [83]. Unlike the E-PRTR, the EU ETS frequently reports multiple technical units within a single industrial complex separately, resulting in a more detailed representation of industrial activities but requiring additional aggregation and harmonization [83]. Together, both databases provide a robust and spatially consistent basis for identifying industrial production sites across the European Union.

The methodology was developed and tested for the European glass, aluminum, and paper industry, for which no dedicated open-source database with comprehensive site coverage was available. First, sector-specific facilities were identified using activity codes defined in the respective reporting systems. Since the E-PRTR reports individual greenhouse gases rather than aggregated CO_2-equivalent emissions, emissions were converted into CO_2 equivalents using the corresponding global warming potentials.

To combine both databases, a multi-stage matching procedure based on geographic coordinates, postal codes, operator names, and facility names was applied. Because facility names frequently differ between databases, fuzzy matching was used to identify likely matches despite variations in spelling and naming conventions. Where information was available from both sources, EU ETS records were prioritized due to their broader coverage and more detailed emissions reporting [83, 84].

As neither database provides production capacities or plant ages, these attributes were reconstructed using additional assumptions. Production volumes were estimated from reported emissions and process-specific emission factors following:

$$P(t) = \frac{E_{\text{total}}}{EF}, \tag{3.15}$$

where $P(t)$ denotes annual production, E_{total} total site emissions, and EF the technology-specific emission factor. Information on plant age is not available in either the E-PRTR or EU ETS databases. However, the age distribution of industrial assets is an important input for technology diffusion modeling, as investment and retirement decisions are linked to the remaining lifetime of existing production units. To approximate plant ages, a synthetic age distribution was generated based on the assumed technical lifetime of each production process. For facilities with unknown commissioning dates, the construction year was randomly assigned within a feasible interval bounded by the model base year and the maximum technical lifetime of the respective process. Specifically, the earliest possible construction year t_u was determined as

$$t_u = t_0 - L_{\max}, \tag{3.16}$$

where t_0 denotes the model base year and $L_{\max}$ the maximum technical lifetime of the process. Construction years were then sampled from the interval $[t_u, t_0]$, resulting in a realistic distribution of plant ages while avoiding the assignment of facilities that would already have exceeded their technical lifetime at the beginning of the simulation period. Although this approach introduces additional uncertainty, it enables the representation of age-dependent reinvestment cycles in the absence of publicly available plant-age information.

The resulting methodology provides a transferable framework for extending open industrial site databases beyond sectors covered by dedicated plant inventories. By combining legally reported emissions data with systematic data harmonization and matching procedures, the approach enables the creation of consistent site-level datasets that can subsequently be integrated into industrial transformation models.

Hydrogen network development Hydrogen network availability is represented using data from the European Hydrogen Backbone (EHB), a consortium-led infrastructure scenario developed by European gas transmission system operators [85, 86]. The EHB provides a geospatially explicit outlook for a future European hydrogen transport network, including projected pipeline corridors, commissioning years, and distinctions between newly built hydrogen pipelines and repurposed natural gas infrastructure. In addition, the EHB reports techno-economic assumptions for different pipeline types, including capital expenditure and fixed operating expenditure. These data are used to approximate the timing and spatial availability of hydrogen pipeline access for industrial sites. In the model, each site is therefore evaluated relative to the nearest available EHB pipeline segment in a given year, allowing hydrogen infrastructure constraints to be represented at the site level rather than only through national or regional assumptions.

Figure 3.4 provides a spatial overview of the steel and chemical industrial sites included in the database and their relation to the projected European hydrogen network. The site markers represent the primary steel and chemical production facilities considered in the model, while the pipeline layers indicate the hydrogen infrastructure corridors reported by the European Hydrogen Backbone. The Figure illustrates the strong spatial clustering of industrial demand around existing production regions, as well as the uneven proximity of sites to future hydrogen transport infrastructure. It therefore highlights why hydrogen availability is treated as a site-specific constraint rather than as a purely national or sectoral assumption.

3.2 iSTEDS

A central methodological outcome of the DEIMOS project is the development and continuous extension of the industrial Spatial and Temporal Energy Demand Simulation model (iSTEDS). The model was designed to investigate long-term decarbonization pathways of the European industrial sector and serves as the common analytical foundation for several of the project's scientific outputs. In contrast to many established industrial energy demand models, which are often only partially documented or not publicly accessible, iSTEDS follows an open-science approach. The model code, methodology, and input datasets have been published as open-source resources, enabling transparency, reproducibility, and further development by the research community [87].

Methodologically, iSTEDS combines top-down and bottom-up modeling approaches in a hybrid framework, as presented in Figure 3.5. Industrial activity is represented at the level of industrial subsectors, applications, and production processes, thereby balancing

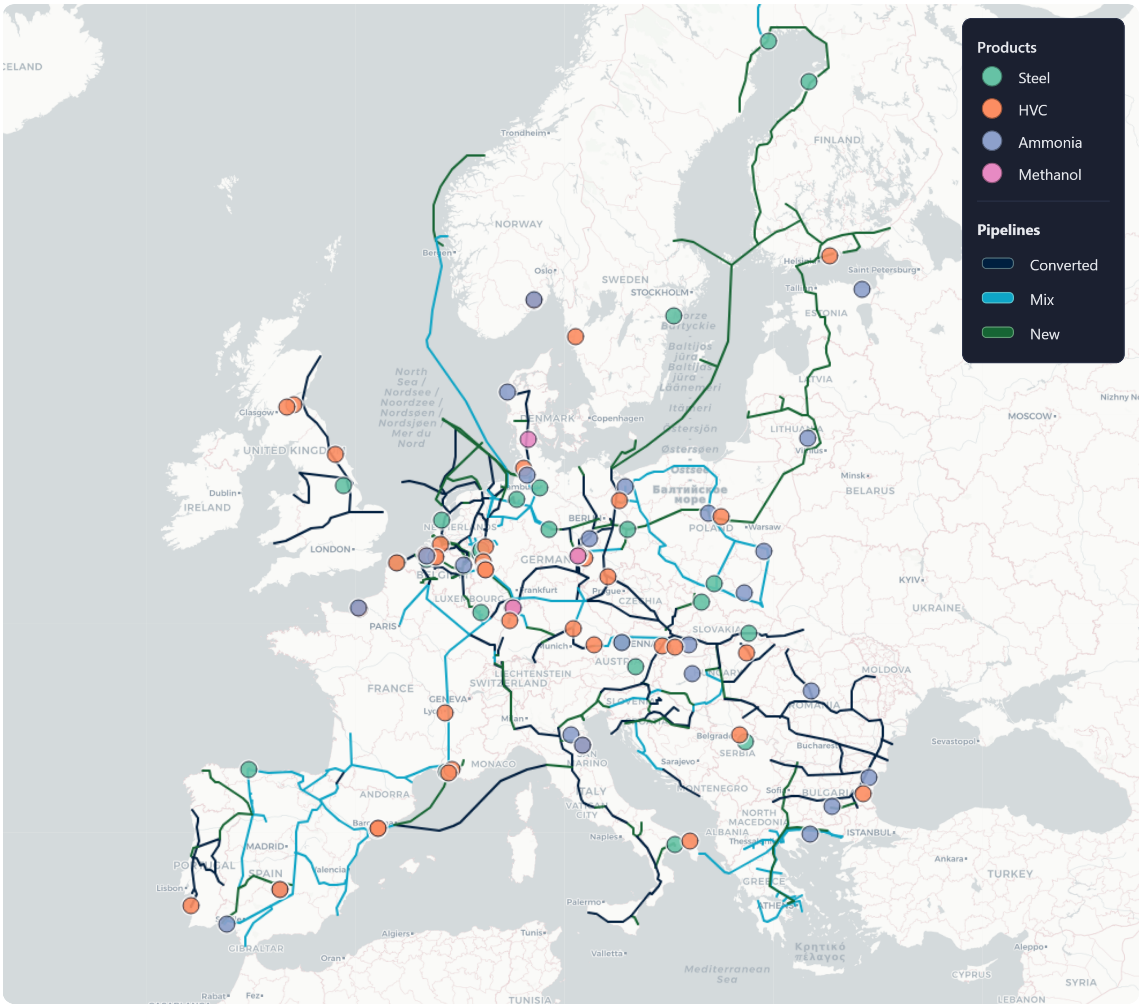

Figure 3.4. *Modelled primary steel and chemical production sites and projected European hydrogen pipeline network in 2050 based on the European Hydrogen Backbone.*

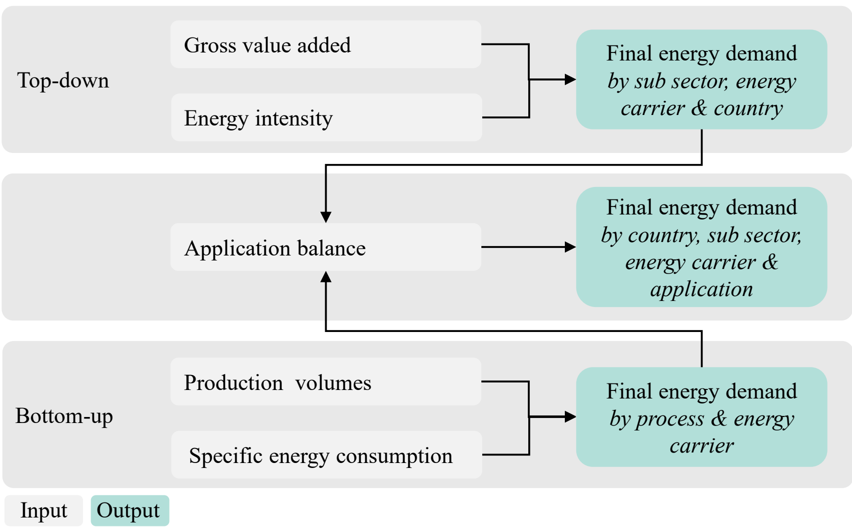

Figure 3.5. *Illustration of the top-down and bottom-up structure in iSTEDS.*

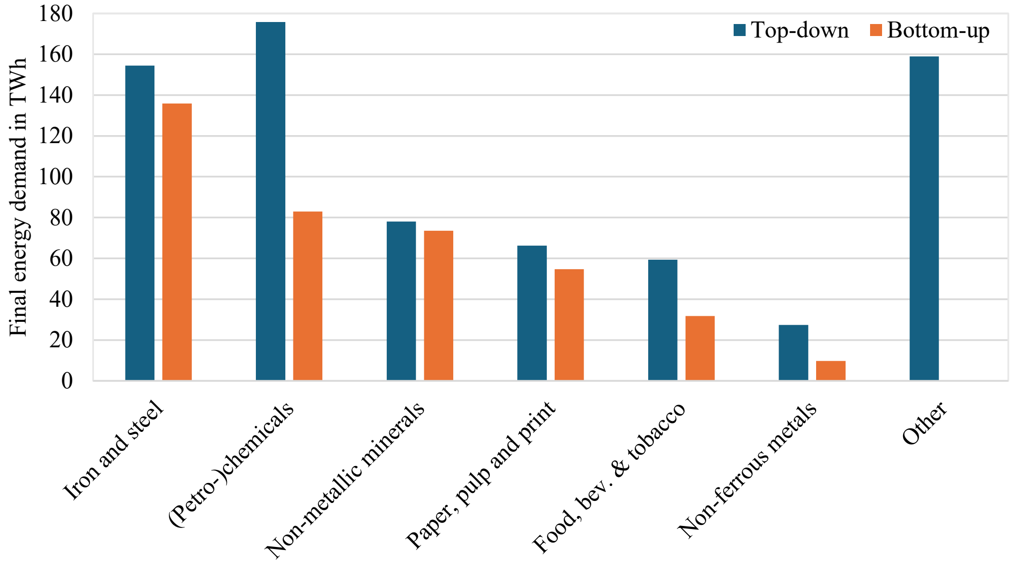

FIGURE 3.6. *Top-down and bottom-up final energy demand covered by the industry demand simulation model by sub-sector in Germany 2019. Own visualization.*

technological detail with comprehensive coverage of European industry. As presented by 3.6, the bottom-up approach accounts for a share of the total final energy demand of 88% in the iron and steel sector, 47% for the production of (petro-)chemicals, 94% of non-metallic minerals, 83% of pulp, paper, and print, 53% of food, beverages, and tobacco, and 36% of the non-ferrous metals production. The geographical scope covers the EU27 plus Norway, Iceland, and the United Kingdom. The model includes 13 industrial sub sectors (top-down), 16 reference processes (bottom-up), and 13 applications, including industrial process heat and cold at different temperature intervals, and cross-sectional technologies. The 16 reference processes represent the industry technologies in the starting year of the model, while additional processes can be introduced endogenously to account for the diffusion of innovative technologies. This is illustrated in Figure 3.7 for aluminum production, where the primary and secondary routes dominate initially and are gradually complemented or replaced by new technologies such as Hall-Héroult with inert anodes, kaolinitic reduction, and carbothermic reduction. Scenario computation[3] follows the modeling approach of the sectoral industry model SmInd [34].

The geographical scope covers the EU-27, Norway, Iceland, and the United Kingdom. Depending on data availability, industrial processes are represented either through detailed bottom-up process models or through top-down sectoral representations, allowing the model to combine open industrial production data with technology-specific information on energy consumption, emissions, and mitigation options. The resulting framework can be used to assess future developments in industrial energy demand, technology diffusion, greenhouse gas emissions, and flexibility provision under different transformation scenarios until 2050.

Within the DEIMOS project, iSTEDS formed the methodological basis for both the carbon capture technology diffusion analysis presented in Case Study B and the techno-

[3]See Hübner (2020) for a comprehensive overview of measure computations.

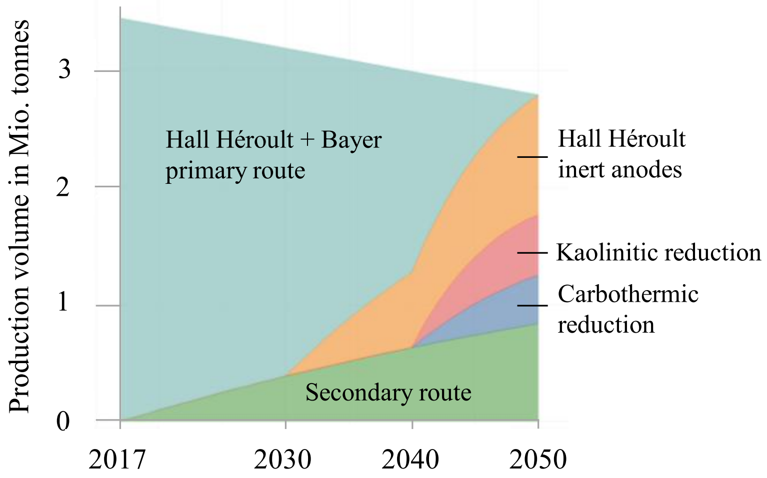

FIGURE 3.7. *Technology diffusion in the aluminum production route in the ambitious decarbonization scenario. Published in Scharnhorst et al. [73].*

economic assessment of future industrial demand-side flexibility potentials presented in Case Study C. While the flexibility assessment builds directly on the core industry simulation model and its scenario results, the carbon capture study extends the framework through an additional technology diffusion module that represents competition between alternative carbon capture technologies. Together, these studies demonstrate the flexibility of the modeling framework and its applicability to different aspects of industrial decarbonization. A detailed description of the model structure and underlying assumptions is provided in [73] and the associated open-source model repository [87].

3.2.1 Carbon-capture technology diffusion module

To investigate the potential role of carbon capture technologies (CCTs) in the decarbonization of Europe's hard-to-abate industries, a dedicated technology diffusion module was developed and integrated into the industrial energy demand simulation model iSTEDS [73]. The approach focuses on process routes with significant residual process emissions, including cement, lime, ammonia, methanol, and primary steel production.

Within the iSTEDS framework, emission reductions are first achieved through material efficiency measures, process route changes, application-specific measures, and energy efficiency improvements. Carbon capture technologies are subsequently applied to the remaining emissions that cannot be avoided through these strategies. These residual emissions comprise both unavoidable process-related emissions and emissions resulting from the use of fossil energy carriers.

The diffusion of carbon capture technologies is modeled as an annual three-step process:

1. Calculation of technology-specific CO_2 capture costs,
2. Determination of technology market shares using a logit-based diffusion model,
3. Updating technology costs through endogenous learning effects.

These steps are detailed in the following.

CO_2 capture cost calculation The adoption of carbon capture technologies is driven by their specific CO_2 capture costs. Following Roussanaly et al. [88, 89], capture costs are calculated using a discounted cash-flow approach and expressed in EUR per tonne of CO_2 captured:

$$C^{CC}_{pr,\gamma}(t) = \frac{C^{CE}_{pr,\gamma} + C^{down}_{pr,\gamma} + \sum_i \frac{C^{op}_{pr,\gamma}(t)}{(1+d)^i}}{\sum_i \frac{E_{captured}(t)}{(1+d)^i}} \tag{3.17}$$

where (pr) denotes the industrial process route and γ the applied carbon capture technology. The calculation includes capital expenditures, retrofit and downtime costs, operational expenditures, transport costs, storage costs, and residual CO_2 certificate costs. A project lifetime of 25 years and a discount rate of 8% are assumed.

Technology diffusion The calculated capture costs are translated into technology market shares using a multinomial logit model. This approach allows multiple competing carbon capture technologies to coexist and compete based on their economic attractiveness.

$$MS_j(t) = \frac{\frac{\exp\left(-lp \cdot C^{CC}_j(t) \cdot \left(\overline{C^{CC}_g(t)}\right)^{-1}\right)}{n^{CCT}_g}}{\sum_g \sum_{k \in g} \frac{\exp\left(-lp \cdot C^{CC}_k(t) \cdot \left(\overline{C^{CC}_g(t)}\right)^{-1}\right)}{n^{CCT}_g}} \tag{3.18}$$

where $MS_j(t)$ denotes the market share of technology j, lp is the logit parameter, and n^{CCT}_g represents the number of technologies within a technology group. The considered technology groups comprise post-combustion, pre-combustion, oxyfuel, and looping technologies.

Unlike deterministic least-cost approaches, the logit formulation allows several technologies to be adopted simultaneously and better reflects heterogeneous industrial investment behavior.

Endogenous technology learning To account for technological progress, the model includes endogenous learning effects. Capital expenditures decrease as cumulative installed capacity increases according to a one-factor learning curve formulation:

$$C^{CE} = C^{CE}_0 \cdot \left(\frac{M_j(t-1)}{M_j(0)}\right)^{\frac{\ln(1-LR)}{\ln(2)}} \tag{3.19}$$

where C^{CE}_0 denotes the initial capital expenditure, M_j the cumulative installed capacity of technology j, and LR the assumed learning rate. A learning rate of 10% is applied following Rubin et al. [90] and Li et al. [91]. Through this feedback mechanism, early deployment reduces future investment costs and thereby increases the competitiveness of technologies in subsequent simulation years.

Scenario assumptions The model is applied to a reference scenario representing current European climate policy trajectories until 2050. The scenario includes projections for energy carrier prices, CO_2 certificate prices, production volumes, and process-specific emissions. To assess the influence of energy market developments on carbon capture deployment, an additional sensitivity scenario with lower future electricity prices is evaluated. The resulting technology diffusion pathways are analyzed for multiple industrial sectors and carbon capture concepts.

3.2.2 Process-flexibility module

The methodology for calculating the demand response potential draws upon the methods outlined in Gils [6] and Steurer [92], encompassing both technical and economic assessments of negative and positive flexibility potentials.

Technical process flexibility potential The installed capacity $P_{\text{installed},i,cr}$ of process (i) in country (cr) is derived from the annual electricity demand $W_{i,cr}$, the number of hours per year N_{hours}, the utilization factor u_i, and the revision share s_i^{revision},

$$P_{\text{installed},i,cr} = \frac{W_{i,cr}}{N_{\text{hours}} \cdot u_i \cdot \left(1 - s_i^{\text{revision}}\right)} \tag{3.20}$$

Following [6], the revision share is assumed to be 5%. The maximum available capacity is then given by

$$P_{\max,i,cr} = P_{\text{installed},i,cr} \cdot \left(1 - s_i^{\text{revision}}\right) \tag{3.21}$$

The minimum capacity is determined using the positive flexibility factor s_i^{pos}:

$$P_{\min,i,cr} = P_{\text{installed},i,cr} \cdot s_i^{\text{pos}} \tag{3.22}$$

Hourly process load is calculated using a normalized load profile $s_{\text{load},i,cr}(t)$:

$$P_{i,cr}(t) = s_{\text{load},i,cr}(t) \cdot W_{i,cr} \tag{3.23}$$

The positive flexibility potential is obtained from the difference between the actual load and the minimum capacity:

$$FP_{\text{pos},i,cr}(t) = P_{i,cr}(t) - P_{\min,i,cr} \tag{3.24}$$

Analogously, the negative flexibility potential is calculated as

$$FP_{\text{neg},i,cr}(t) = \left(P_{\max,i,cr} - P_{i,cr}(t)\right) \cdot s_i^{\text{neg}} \tag{3.25}$$

Deriving hourly flexibility costs The hourly flexibility costs comprise investment costs, fixed and variable operation costs, as well as flexibility provision costs. Following [92], the investment costs of process (i) consist of information and communication technology (ICT) costs $C_{\text{ICT},i}$ and implementation costs $C_{\text{imp},i}$. Specific investment costs are derived

TABLE 3.1. *Input data on positive and negative flexibility potentials by production process.*

Process	s_i^{pos}	s_i^{neg}	**Ref.**
EAF	0	0	[93, 94]
DRI-EAF	0.3 (DRI) 0 (EAF)	0	[93]
H_2-DRI-EAF	0 (H_2) 0.3 (DRI) 0 (EAF)	0	[93]
Ammonia (Haber–Bosch process)	0.2	1	[95]
Ammonia electrolysis	0.1	1	[95]
Methanol electrolysis[a]	0.1	1	–
Aluminium electrolysis	0.75	0	[6]
Aluminium HH inert anodes[b]	0.75	0	–
Aluminium carbothermic reduction[b]	0.75	0	–
Aluminium kaolinitic reduction[b]	0.75	0	–
Container glass	0.67	1	[96]
Flat glass	0.67	1	[96]
Cement	0.5	1	[6]
Paper	0.7	1	[6]
Meat	0	1	[97]
Milk[c]	0	1	–
Baked goods[c]	0	1	–
Sugar	0	1	[98]

[a] For methanol electrolysis, the same flexibility potentials are assumed as for ammonia electrolysis.
[b] The same potentials as for aluminium electrolysis are assumed, as these decarbonization processes are allocated to the primary aluminium production route.
[c] For milk and baked goods, the same flexibility potential as for meat is assumed due to similar cooling requirements and unavailable process-specific data.

by dividing total investment costs by the technical flexibility potential $FP_{\text{tech},i}$:

$$c_{\text{inv,spec},i} = \frac{C_{\text{ICT},i} + C_{\text{imp},i}}{FP_{\text{tech},i}} \tag{3.26}$$

The provision costs are calculated separately for positive and negative flexibility:

$$C_{\text{prov},i,cr}(t) = \frac{1}{24}(c_{\text{prov,pos},i} \cdot FP_{\text{pos},i,cr}(t) + c_{\text{prov,neg},i} \cdot FP_{\text{neg},i,cr}(t)) \tag{3.27}$$

Variable costs arise from labor, material, or energy expenditures and differ between load shifting and load shedding. Hourly variable costs are calculated as:

$$C_{\text{var,lshift/lshed},i,cr}(t) = c_{\text{var,lshift/lshed},i} \cdot \left(FP_{\text{pos},i,cr}(t) + FP_{\text{neg},i,cr}(t)\right) \tag{3.28}$$

The total hourly flexibility costs are obtained by summing investment-related costs, fixed operation and maintenance costs, variable costs, and flexibility provision costs.

Techno-economic parameters Future hourly electricity demand until 2050 is derived from an industrial demand simulation model for two scenarios: a Reference Scenario (RS) and a Target Scenario (TS). The RS assumes continuation of current trends, including energy efficiency improvements but no additional sector-specific decarbonization measures. The TS represents an ambitious decarbonization pathway incorporating energy carrier substitution, circular economy measures, material efficiency improvements, and process route changes.

In total, 127 decarbonization measures are implemented across 16 industrial processes, 13 applications, and 13 industrial sub sectors for the EU-27, Norway, Iceland, and the United Kingdom. Model outputs provide annual electricity demand projections, which are subsequently allocated to synthetic hourly load profiles for the 15 industrial processes identified as having technical flexibility potential. The process-specific load profiles were derived from open databases [99], scientific literature, and industrial project reports [100, 101]. The profiles were synthesized with respect to representative days, public holidays, and seasonal variations for the EU-27, Norway, Iceland, and the United Kingdom until 2050. The resulting flexibility assumptions are summarized in Table 3.1.

If $s_i^{\text{pos}} = 0$, the process can be completely shut down. Conversely, a negative flexibility potential of $s_i^{\text{neg}} = 0$ indicates that the process either already operates at maximum capacity or cannot increase its load due to technological constraints, such as temperature requirements [102].

Table 3.1 presents the process-specific costs associated with flexibility provision. It should be noted that provision costs are explicitly reported only by Steurer (2017) [92], whereas other studies mainly provide fixed annual costs. Therefore, it is assumed that provision costs are implicitly included in the reported fixed costs in these studies [96, 103]. For the DRI-EAF and H_2-DRI-EAF routes, the same flexibility provision costs are assumed as for the conventional EAF route.

4 Three case studies on industrial transformation pathways

The following chapter presents three exemplary case studies that illustrate the capabilities of the modelling frameworks developed within the DEIMOS project. Together, the case studies address different dimensions of industrial transformation, including technology adoption, carbon capture deployment, and industrial demand-side flexibility. The analyses draw on both the FORECAST-Sites Extended and iSTEDS models and demonstrate how open-source industrial datasets can be combined with techno-economic modelling approaches to investigate long-term decarbonization pathways in Europe. While each case study focuses on a specific research question and sectoral context, collectively they showcase the potential of the developed frameworks to analyse industrial technology diffusion, infrastructure requirements, emissions mitigation strategies, and the interaction between industrial transformation and future energy systems.

4.1 Case study A: Hydrogen pathways for the European steel and chemical sectors (FORECAST-Sites Extended)

This case study presents a baseline, or "business as usual" scenario for the uptake of hydrogen-based technologies in the European steel and chemical sectors until 2050. The scenario assumes that current trends in energy and technology prices continue; the scenario also assumes that the hydrogen pipeline network develops according to the European Hydrogen Backbone's baseline scenario [86]. The site-level input data is described in Section 3.1.2 above; the methodology underlying the additional input data, e.g. energy prices, technology prices, is described in the accompanying publication [104].

4.1.1 Results

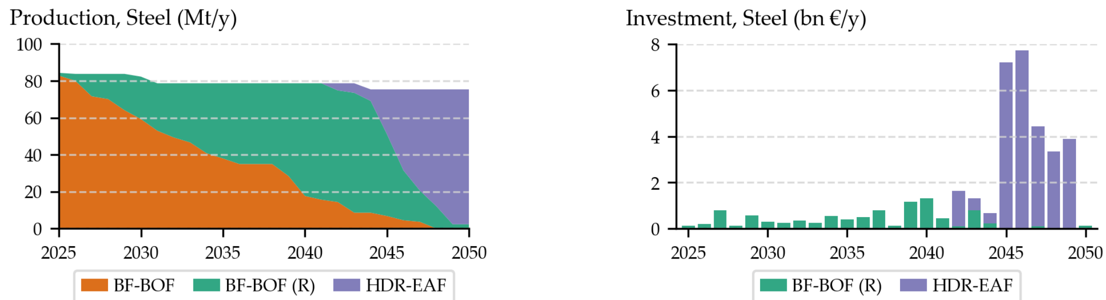

FIGURE 4.1. *EU-wide development of primary steel production and investment in newly installed processes.*

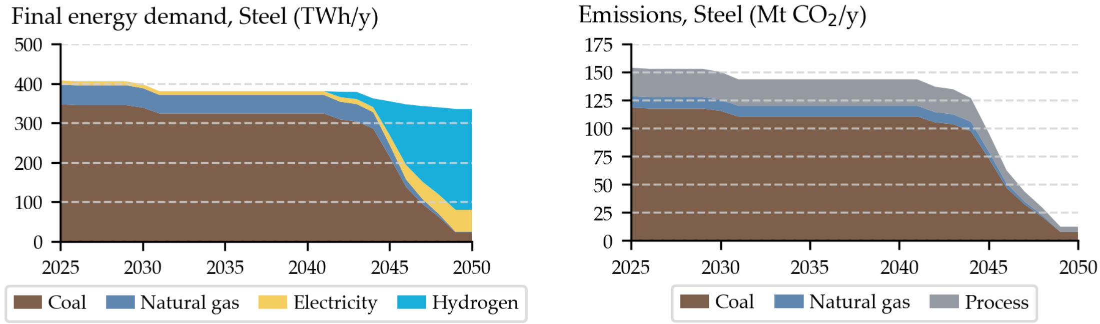

FIGURE 4.2. *EU-wide development of energy demand and direct emissions in primary steel production.*

Steel In the baseline, steel production declines only moderately, from about 84.3 Mt/y in 2025 to 75.4 Mt/y by 2050. The decline is selective: roughly 9.0 Mt/y of 2025 production exits, while 41 units, representing 75.4 Mt/y, remain in operation. Retirements are concentrated in older BF-BOF units in France, Austria, Slovakia, Poland, the United Kingdom, Germany, and Sweden. Surviving capacity is dominated by Germany, with substantial remaining volumes in the Netherlands, France, Belgium, Spain, Italy, Sweden, Austria, Finland, Poland, and Czechia. The main driver is asset vintage and reinvestment timing: retired units have an average last reinvestment year around 1988, compared with about 2016 for surviving units.

The investment pattern follows a two-stage pathway. Through the 2030s and early 2040s, investment is mainly directed toward incremental BF-BOF retrofits. Once hydrogen infrastructure is accessible, deployment shifts rapidly toward HDR-EAF, with annual investment peaking at about 7.2-7.7 bn €/y in 2045-2046. However, the hydrogen network constraint leaves a small residual role for BF-BOF retrofits: two surviving units, about 2.3 Mt/y in total, remain on BF-BOF (R) in 2050 because their pipeline distances exceed the connection threshold. As a result, HDR-EAF reaches about 73.1 Mt/y by 2050 rather than fully replacing all surviving steel capacity.

The energy and emissions profiles therefore show a sharp late transition, but not complete elimination of fossil-based operation. Coal use falls from about 347 TWh in 2025 to 23 TWh in 2050, while hydrogen rises to about 255 TWh and electricity to about 56 TWh. Emissions decline from roughly 154 Mt CO2/y in 2025 to about 12 Mt CO2/y in 2050, with the remaining emissions mainly associated with residual BF-BOF retrofit capacity. The baseline therefore describes a delayed and compressed steel transition, with hydrogen access determining which surviving units can complete the switch to HDR-EAF.

Ammonia In the baseline, ammonia production contracts from about 12.1 Mt/y in 2025 to 7.0 Mt/y by 2040, and remains broadly stable thereafter. As before, this decline reflects selective capacity retirement rather than a uniform reduction across the sector. Around 5.1 Mt/y of 2025 production exits by 2040, concentrated in a small number of large, older plants in Austria, the Netherlands, Germany, Italy, Belgium, Poland, Hungary, and Slovakia. Surviving capacity is more geographically dispersed, with the largest remaining volumes in Germany, Poland, and Lithuania. The main driver is reinvestment timing:

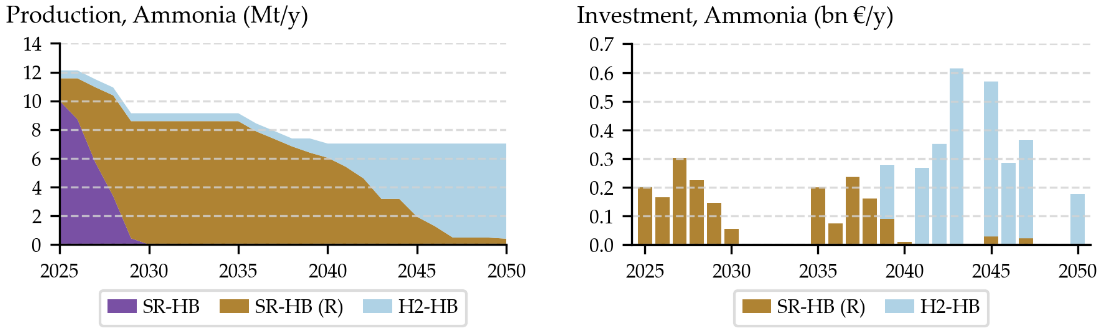

FIGURE 4.3. *EU-wide development of ammonia production and investment in newly installed processes.*

retired units are larger and older on average, with a mean last reinvestment year around 2005, compared with about 2013 for surviving units.

Investment follows a staged transition. Early spending is directed toward SR-HB retrofits, but only where reinvestment remains economically justified. From the early 2040s, investment shifts toward H2-HB as hydrogen-based ammonia becomes more competitive and hydrogen infrastructure access improves, with annual H2-HB investment peaking at about 0.6 bn €/y in 2043. The stricter network-access constraint leaves a small residual role for gas-based production: about 0.41 Mt/y remains on SR-HB (R) in 2050, located in two units in France and Estonia whose hydrogen connection is not available within the distance threshold. H2-HB therefore reaches about 6.6 Mt/y by 2050, rather than fully replacing all surviving ammonia capacity.

The energy, feedstock, and emissions trajectories reflect both capacity selection and technology substitution. Natural gas feedstock falls from about 67 TWh in 2025 to 2.4 TWh in 2050, while hydrogen feedstock rises to about 43 TWh. Final energy demand shifts from natural gas toward electricity, with electricity increasing to about 11 TWh by 2050 and residual natural gas falling to about 1.3 TWh. Total emissions decline from roughly 13.2 Mt CO2/y in 2025 to about 1.3 Mt CO2/y in 2050. The baseline therefore describes a smaller ammonia sector largely rebuilt around H2-HB, with a small residual gas-based segment where hydrogen access remains constrained.

Methanol In the baseline, methanol production remains constant at about 2.33 Mt/y from 2025 to 2050. The sector is small and highly concentrated: nine units remain in operation throughout the period, with seven German units accounting for about 2.29 Mt/y of output and two small units in Denmark and Iceland accounting for the remainder. Five German SR-MP units represent almost all initially gas-based production, while four small H2-MP units are already present at the start of the simulation. The sectoral pattern is therefore not driven by capacity retirement, but by the synchronized conversion of a small number of German assets.

Investment occurs in two short phases. Initial spending is directed toward SR-MP retrofits in the late 2020s, preserving the existing gas-based production base. A second, larger wave follows in the mid-2030s, when the main German units switch to H2-MP; annual investment peaks at about 0.25 bn €/y in 2037. This timing reflects the improving economics of hydrogen-based methanol production. H2-MP remains relatively costly at

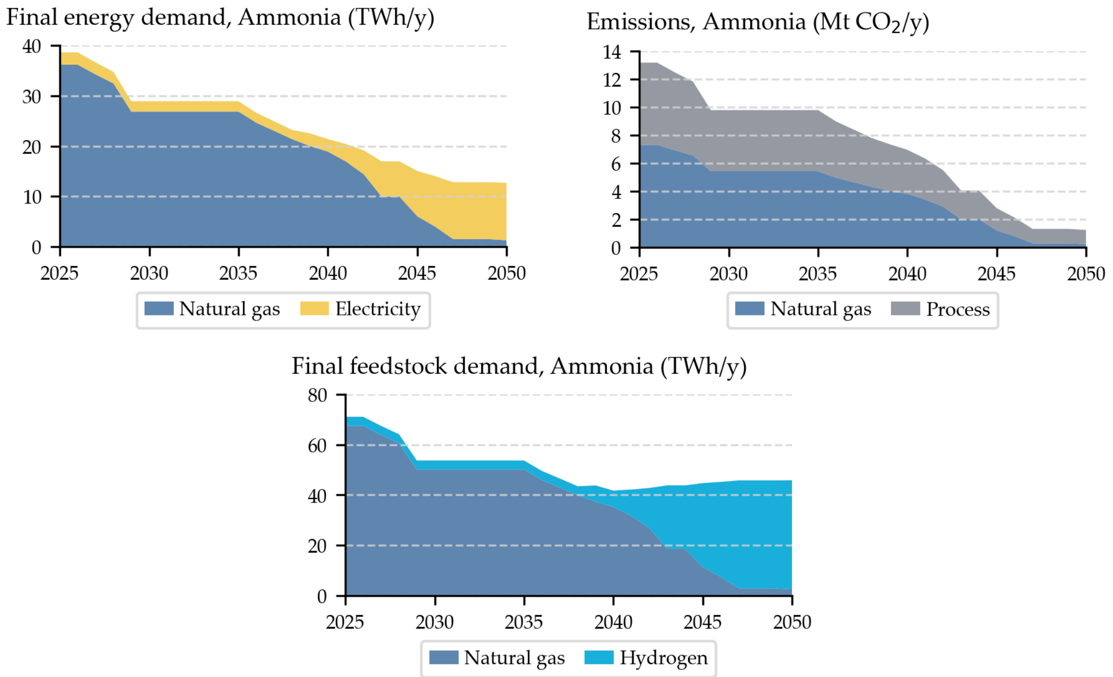

FIGURE 4.4. *EU-wide development of energy demand, direct emissions, and feedstock demand in ammonia production.*

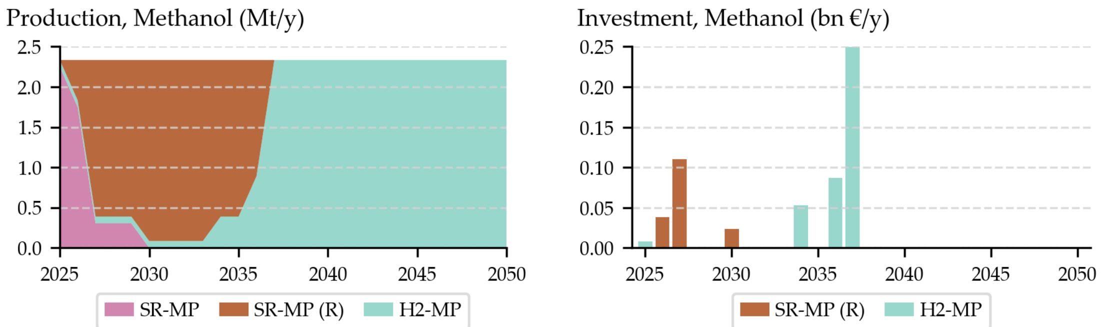

FIGURE 4.5. *EU-wide development of methanol production and investment in newly installed processes.*

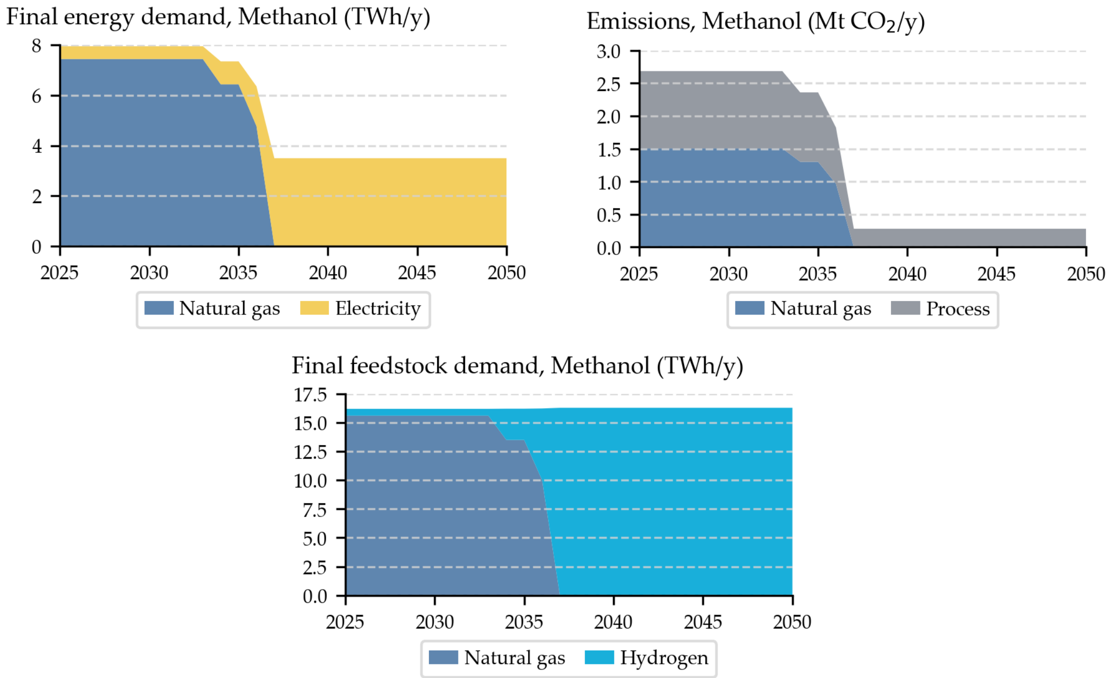

FIGURE 4.6. *EU-wide development of energy demand, direct emissions, and feedstock demand in methanol production.*

the start of the period, but its production cost falls from about 861 €/t in 2025 to about 654 €/t by 2037 and 515 €/t by 2050. The hydrogen network constraint does not leave residual gas-based capacity in this sector, so all methanol production is converted to H2-MP by 2037.

The energy, feedstock, and emissions trajectories show a complete fuel and feedstock substitution without any loss of output. Natural gas feedstock falls from about 15.6 TWh in 2025 to zero after conversion, while hydrogen feedstock rises to about 16.3 TWh. Final energy demand shifts from roughly 7.5 TWh of natural gas in 2025 to about 3.5 TWh of electricity after 2037. Energy-related emissions are eliminated, and total emissions fall from about 2.7 Mt CO2/y in 2025 to around 0.3 Mt CO2/y from 2037 onward, reflecting residual process emissions. The methanol baseline therefore represents a compact, infrastructure-enabled conversion pathway rather than a restructuring or contraction of the sector.

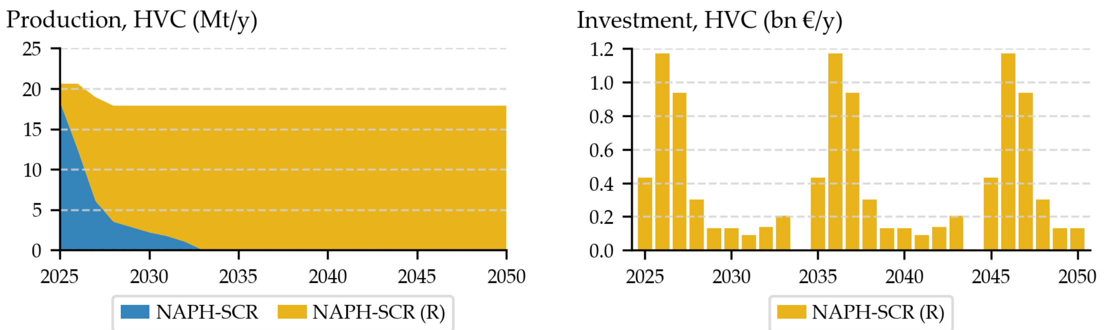

FIGURE 4.7. *EU-wide development of HVC production and investment in newly installed processes.*

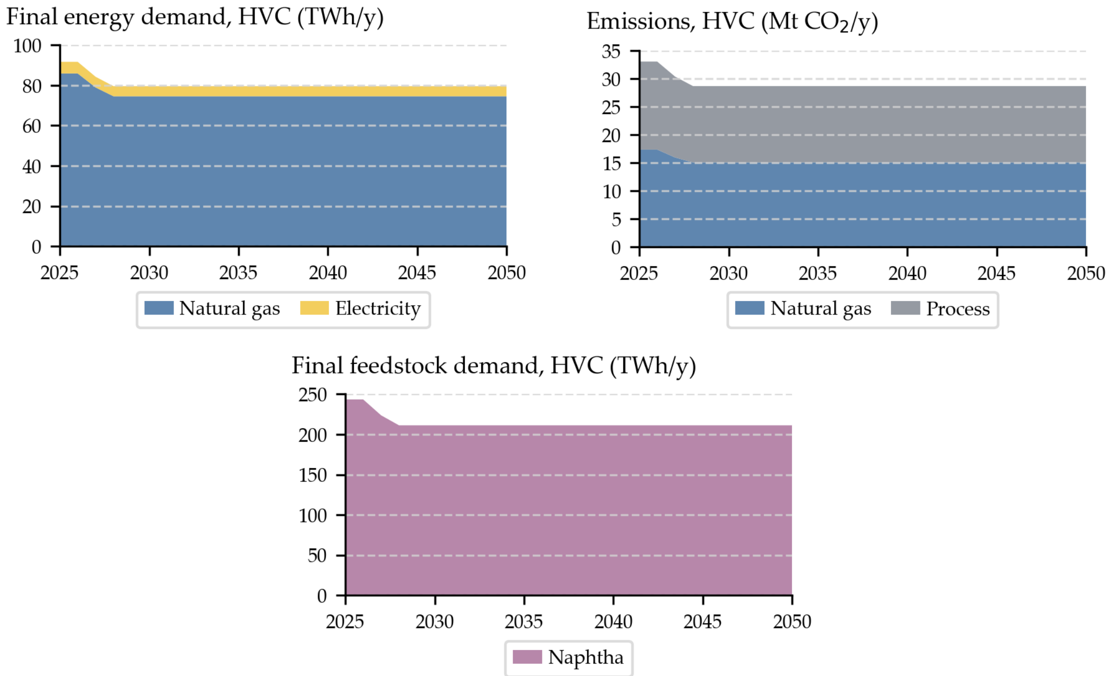

FIGURE 4.8. *EU-wide development of energy demand, direct emissions, and feedstock demand in HVC production*

HVC In the baseline, HVC production declines from about 20.6 Mt/y in 2025 to 17.9 Mt/y by 2030, and remains constant thereafter. This contraction reflects the retirement of around 2.7 Mt/y of capacity, concentrated in a small number of units in Spain, Germany, Portugal, France, Slovakia, and Switzerland. Surviving production is geographically dispersed but led by Germany, Belgium, the United Kingdom, France, and the Netherlands. The vintage effect is present but weaker than in steel or ammonia: retired units have an average last reinvestment year around 2000, compared with about 2011 for surviving units. The dominant pattern is therefore not structural transformation, but continued operation of the incumbent naphtha-cracking route.

Investment is entirely directed toward NAPH-SCR retrofits. The repeated investment peaks around 2026-2027, 2035-2037, and 2045-2047 reflect the 10-year retrofit lifetime rather than the deployment of a new low-carbon route. H2-MTO is not adopted because it remains far more expensive than continued naphtha cracking. Its capital cost is about 1190 €/t, compared with about 200 €/t for NAPH-SCR (R), and its annuity burden is more than three times higher. Although H2-MTO has lower base OPEX and lower process emissions, these advantages are outweighed by very high electricity and hydrogen requirements: 21.1 GJ/t of electricity and 68 GJ/t of hydrogen feedstock, compared with 1.0 GJ/t of electricity and 42.5 GJ/t of naphtha for the retrofit route. Even in 2050, H2-MTO production costs remain around 1555 €/t, compared with about 879 €/t for NAPH-SCR (R).

The energy, feedstock, and emissions profiles therefore remain essentially flat after the initial retirements. Naphtha feedstock demand falls from about 243 TWh in 2025 to 211 TWh by 2030 and then remains unchanged. Final energy demand stabilizes at roughly 75 TWh of natural gas and 5 TWh of electricity. Total emissions fall from about 33 Mt

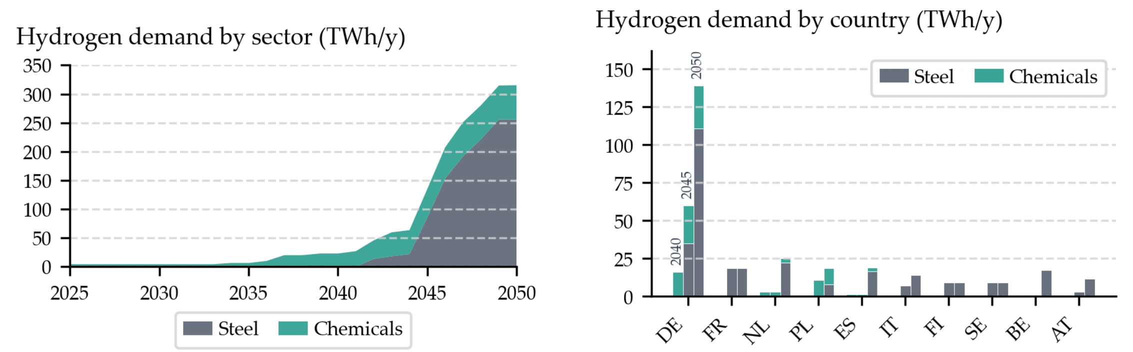

FIGURE 4.9. *Left panel: Hydrogen demand by product over the simulation period 2025–2050. Right panel: Hydrogen demand by country and sector for the years 2040, 2045, and 2050.*

CO2/y in 2025 to around 29 Mt CO2/y by 2030, but do not decline further because the surviving sector remains naphtha-based. HVC is therefore the baseline outlier: hydrogen access does not induce fuel switching because the hydrogen-based route is structurally uncompetitive relative to repeated naphtha-cracker retrofits.

Hydrogen demand & pipeline investment In the baseline, industrial hydrogen demand remains limited through the 2030s but increases sharply once large steel assets begin switching to HDR-EAF. Total demand rises from 22.8 TWh/y in 2040 to 135.1 TWh/y in 2045 and 315.2 TWh/y in 2050. The early market is almost entirely chemical: chemicals account for 22.8 TWh/y in 2040, mainly ammonia and methanol. By 2050, however, steel dominates hydrogen use, reaching 255.5 TWh/y, or 81% of total demand, while chemicals contribute 59.7 TWh/y. The geography is correspondingly concentrated. Germany is the central hydrogen market, rising to 139.2 TWh/y in 2050, of which 110.7 TWh/y is steel and 28.5 TWh/y chemicals. The next largest markets are much smaller: the Netherlands 24.9 TWh/y, Spain 18.8 TWh/y, Poland 18.7 TWh/y, France 18.5 TWh/y, Belgium 17.5 TWh/y, Italy 14.5 TWh/y, and Austria 11.7 TWh/y.

Pipeline investment is therefore lumpy and anticipatory rather than proportional to aggregate hydrogen demand. Cumulative pipeline expenditure is 306 mn € over 2025-2050, with 257 mn €, or 84%, occurring between 2039 and 2044. Annual expenditure

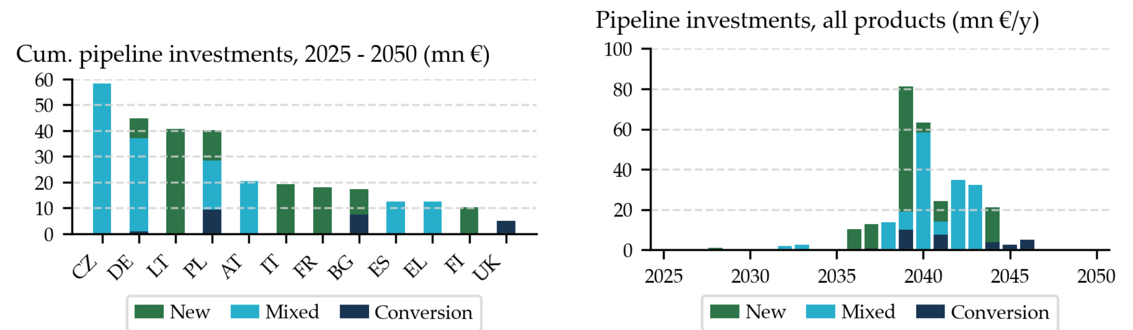

FIGURE 4.10. *Left panel: Cumulative pipeline investment by country and connection type over the simulation period 2025–2050. Right panel: Annual pipeline investment by connection type over all modelled countries.*

peaks at 81 mn € in 2039 and 63 mn € in 2040, ahead of the main increase in hydrogen consumption after 2045. Mixed pipeline routes account for the largest share of cumulative spending, 159 mn €, followed by new hydrogen pipelines at 118 mn € and natural-gas pipeline conversion at 30 mn €. The country pattern reflects site-specific connection costs: Czechia has the highest cumulative investment, 58 mn €, despite modest 2050 hydrogen demand of 8 TWh/y, because the cost is dominated by the single Třinec steel site. Lithuania is similarly concentrated around the Achema ammonia plant, with 41 mn € of new-pipeline investment. Germany, by contrast, has by far the largest hydrogen demand but only 45 mn € of pipeline investment, indicating that several high-demand sites are relatively well positioned with respect to the assumed network. This asymmetry suggests that the main infrastructure challenge is not only the scale of national hydrogen demand, but the location of a small number of large industrial sites relative to feasible network connections.

Sensitivity to the shutdown hurdle rate The sensitivity analysis shows that increasing the shutdown hurdle rate from 5% to 10% does not primarily delay the industrial transformation, but instead converts economically marginal reinvestments into capacity exit. In the steel sector, several production units for which the transition to HDR–EAF provides cost reductions of only around 7–9% no longer satisfy the stricter reinvestment criterion and are therefore shut down. As a result, HDR–EAF production in 2050 decreases from 73.1 to 64.3 Mt/y, while steel-sector hydrogen demand falls from 255.5 to 224.7 TWh/y. A comparable effect occurs in methanol production, where units with cost advantages of approximately 8–10% no longer convert under the stricter hurdle-rate assumption.

4.1.2 Discussion

The case study suggests that industrial decarbonization in Europe is highly uneven across sectors and is driven primarily by asset vintages, reinvestment timing, and access to hydrogen infrastructure. Steel emerges as the dominant source of future hydrogen demand, with a rapid but delayed transition to HDR-EAF occurring mainly after 2040, resulting in substantial emissions reductions but leaving a small residual fossil-based segment where hydrogen access remains constrained. Ammonia follows a similar pattern, albeit with significant capacity contraction alongside partial conversion to hydrogen-based production. In contrast, methanol achieves a complete transition to hydrogen-based production without any loss of output, reflecting favourable economics and a highly concentrated asset base. HVC production is the notable exception: despite hydrogen availability, the hydrogen-based route remains structurally uncompetitive, leading to continued reliance on naphtha cracking and only modest emissions reductions. As a result, industrial hydrogen demand remains limited until the 2040s before rising sharply to more than 300 TWh/year by 2050, driven overwhelmingly by steel. The findings highlight that hydrogen infrastructure influences not only the pace of decarbonization but also which individual sites are able to transition, while sector-specific technology economics ultimately determine whether hydrogen is adopted at all. The hurdle-rate sensitivity highlights that stronger competitive pressure affects not only the timing of technology adoption, but also the retention of industrial production capacity. Under the higher shutdown hurdle, reduced hydrogen demand partly reflects lower surviving production rather than a simple postponement of hydrogen-based investment. The sensitivity therefore indicates that stricter economic requirements can make the transformation pathway smaller rather than merely slower. The analysis is subject to several limitations. First, hydrogen supply is not modelled explicitly; instead, hydrogen is assumed to be produced off-site and available in unlimited quantities at exogenously specified prices. Second, production volumes at each site are fixed throughout the simulation (with the exception of shutdowns), implying that changes in product demand, market structure, or international competitiveness are not considered. Similarly, a range of potentially important economic dynamics, including wage growth, technological learning, and scale effects, are held constant. Third, investment flexibility is limited to the modification, replacement, or retirement of existing production units, while more complex adjustment mechanisms such as the construction of entirely new production sites are excluded. Finally, investment decisions are made under perfect foresight and without uncertainty regarding future costs, policies, infrastructure availability, or technology development. As a result, the model should be interpreted as a deterministic exploration of long-term industrial transition pathways rather than a prediction of actual investment outcomes.

4.2 Case study B: Diffusion of carbon capture technologies in process-emission intensive industries (iSTEDS)

Case study B investigates the diffusion of carbon capture technologies in process emission intensive industries such as the non-metallic minerals sector until 2050. The analysis reflects a reference scenario (RS) that represents current European climate policy trajectories until 2050. Sensitivities to lower future electricity prices are tested in an additional sensitivity scenario (AS). Further information on the methods and results of the case study can be found in the accompanying publication [87].

4.2.1 Results

The following results detail the deployment of CCTs, focusing specifically on the non-metallic minerals sector. Figure 4.11 illustrates the diffusion dynamics for the conventional cement process route between 2020 and 2050, measured by the production volume equipped with each CCT. Meanwhile, Figure 4.12 and Figure 4.13 depict the projections for both conventional lime and lime parallel-flow regenerative kiln routes, respectively. The conventional cement route exhibits the highest overall CCT deployment, with capture-equipped production volumes peaking in 2035. In the RS, Calcium looping tail-end (CAL te.) dominates throughout, reaching 26 Mt in 2035, followed by indirect calcination (low emissions intensity lime and cement, 17 Mt) and oxyfuel technology (17 Mt). Post-2035, CCT volumes decline rapidly as the conventional route phased out in favor of autoclaved

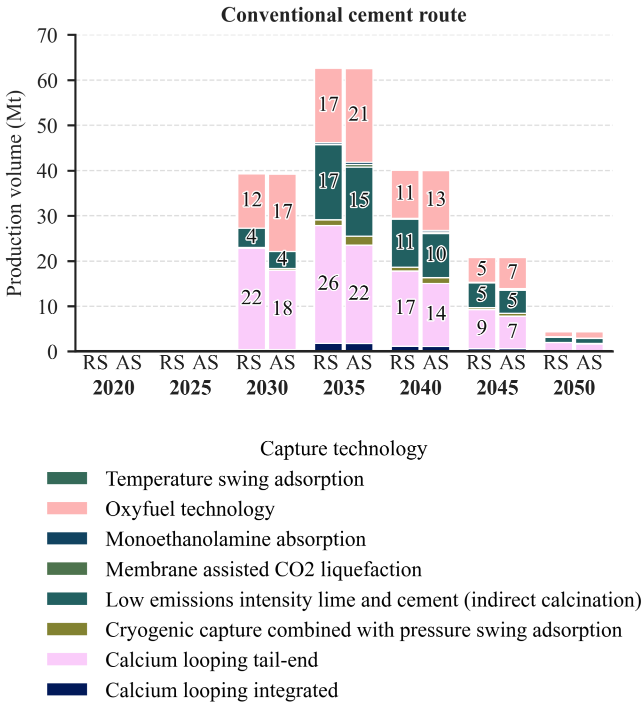

FIGURE 4.11. *Technology diffusion for the conventional cement route. (RS: Reference Scenario, AS: Additional Scenario)*

aerated concrete or belite cement production.

As Figure 4.12 presents, the conventional lime route mirrors this transitional trend, peaking around 2035 at roughly 10 Mt before steadily declining to below 5 Mt by 2050. Calcium looping tail-end dominates the mix throughout, complemented by smaller contributions from low emissions intensity lime and cement (indirect calcination, LEILAC) and oxyfuel technology. The new lime parallel-flow regenerative kiln route represents a growing technology segment, with deployment expanding continuously through 2050 to nearly 20 Mt and fostering a highly diversified mix of CCTs. By 2050, LEILAC leads the market at around 8 Mt, followed by calcium looping tail-end and oxyfuel technology (5 Mt each) with smaller contributions from other capture technologies.

The AS yields only marginal deviations from the RS across all three production routes. The conventional cement route preserves both the 2035 deployment peak and the dominance of calcium looping tail-end, with only minor reallocations among capture technologies. The conventional lime and lime parallel-flow regenerative kiln routes likewise show near-identical trajectories and technology mixes in both scenarios. These results indicate that the modelled CCT diffusion in the non-metallic minerals sector is robust to the assumed partial decoupling of electricity and natural gas prices, being primarily driven by sector-specific techno-economic characteristics rather than the electricity price pathway alone. The simulation results expose a dichotomy in the strategic role of CCTs: they act as temporary bridge for conventional, emission-intensive process routes and serve as permanent mitigation technology for modern processes with inescapable emissions. To provide broader context for these trends, Figure 4.14 details the modelled volumes of captured fuel and process emissions by industrial sector. The non-metallic

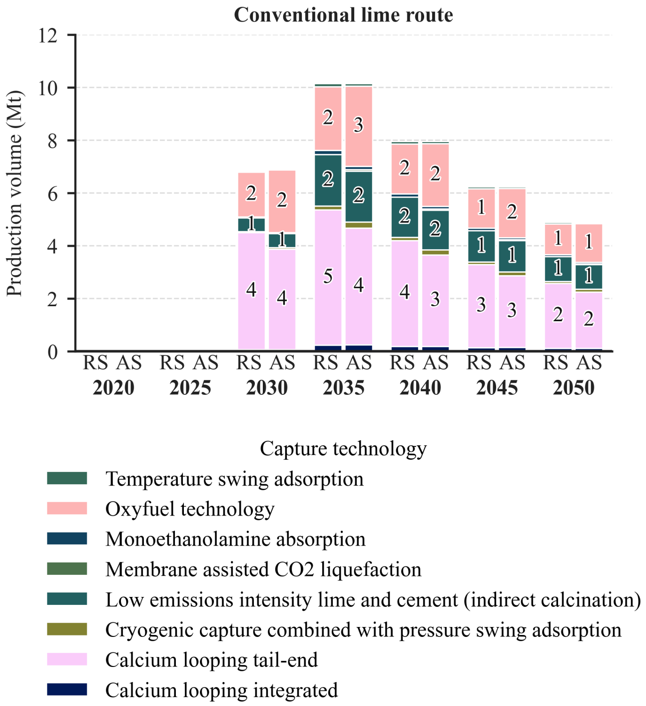

FIGURE 4.12. *Technology diffusion for the conventional lime route. (RS: Reference Scenario, AS: Additional Scenario)*

minerals and primary steel sectors account for the majority of captured fuel emissions. In the RS, total captured fuel emissions peak in 2035 at around 34 Mt, with 19 Mt from non-metallic minerals and 9 Mt from primary steel. The capture of process emissions is dominated by the non-metallic minerals sector across all timeframes and is identical in both scenarios, peaking at 31 Mt in 2035.

4.2.2 Discussion

The objective of this case study was to investigate the potential diffusion of carbon capture technologies (CCTs) in Europe's hard-to-abate industries and to identify promising technology pathways for the mitigation of residual industrial emissions. To this end, the open-source industry simulation model iSTEDS was extended by a dedicated technology diffusion module that combines process-specific CO_2 capture costs, endogenous technological learning, and a logit-based representation of technology adoption. The results highlight that the role of carbon capture strongly depends on the industrial process under consideration. In sectors characterized by unavoidable process emissions, such as lime and cement production, carbon capture emerges as a key long-term decarbonization option. In contrast, for production routes that are expected to be replaced by alternative low-carbon technologies, carbon capture primarily serves as a transitional mitigation measure. Across all analyzed scenarios, calcium looping tail-end technologies, indirect calcination (LEILAC), and oxyfuel concepts were identified as the most relevant capture options in the non-metallic minerals sector and account for the majority of captured emissions. Beyond the specific technology assessment, the study demonstrates

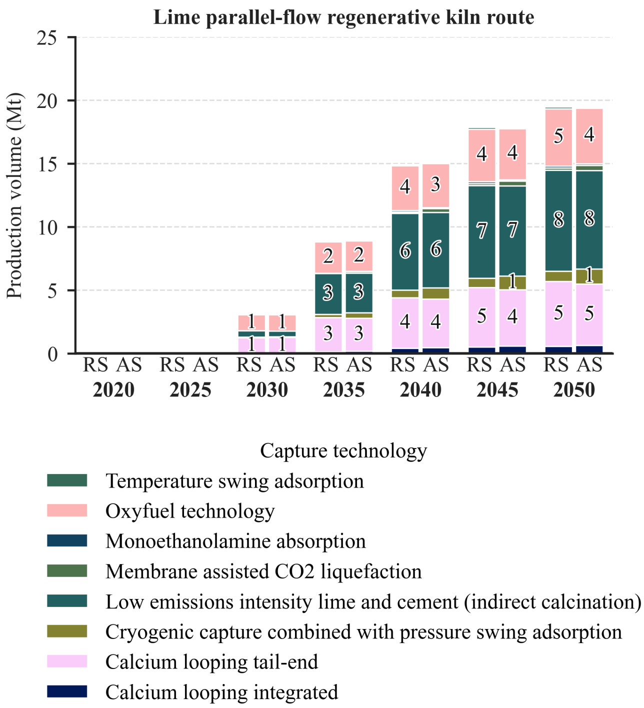

Figure 4.13. *Technology diffusion for the lime parallel-flow regenerative kiln route. (RS: Reference Scenario, AS: Additional Scenario)*

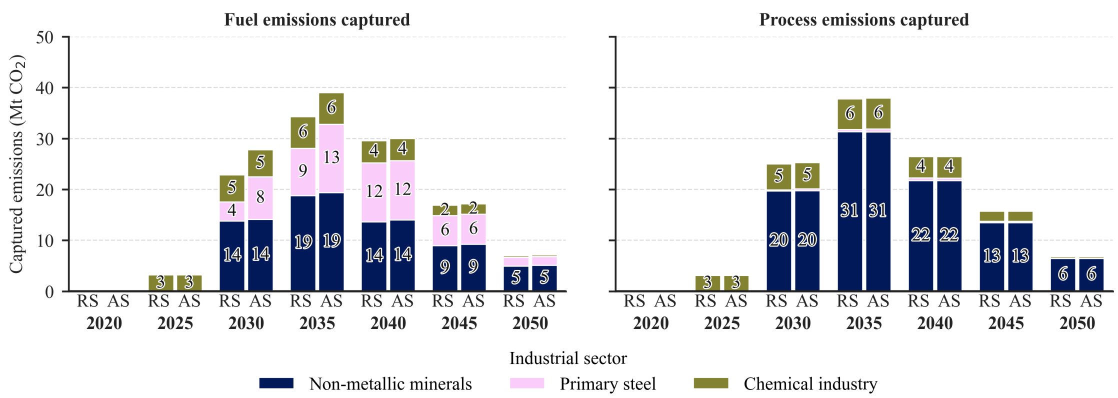

Figure 4.14. *Captured fuel and process emissions. (RS: Reference Scenario, AS: Additional Scenario)*

the applicability of open-science-based technology diffusion modelling for industrial decarbonization analyses and provides a transparent framework that can be extended to additional sectors, technologies, and future research questions.

While the framework to investigate carbon capture technology diffusion provides a structured approach for analyzing technology diffusion, the findings must be interpreted as an exploration of potential pathways rather than exact forecasts, subject to several constraints and simplifications. Notably, the model's rapid CCT uptake by 2035 likely overestimates real-world deployment speed. It assumes frictionless adoption upon technical and economic viability, which partially omits considerable lead times and high project failure rates associated with industrial-scale investments [105]. Furthermore, the model applies a uniform CO_2 certificate price across all evaluated routes. In reality, the EU Emission trade system issues free emission allowances to specific sectors such as steel production, to protect these industries from the full regulatory signal and reduce the risk for carbon leakage. In addition, except for the non-metallic minerals sector, the modeled industrial products act as price-takers globally, adopting highly capital-intensive low-carbon processes puts them at severe economic disadvantage, if equivalent carbon pricing is not enforced worldwide. Moreover, as the input data was collected from diverse literature sources, requiring extensive harmonization as the cost and performance assessment of CCTs lacks standardization, the techno-economic parameters underlying the logit-based technology diffusion module may remain inexact to a certain degree.

4.3 Case study C: Future flexibility potentials in Europe's energy intensive industry (iSTEDS)

Case study C investigates the future industrial demand response potentials for electricity intensive industries, such as steel, chemicals, glass, aluminum and cement production, as well as food products. A Reference Scenario (RS) and a Target Scenario (TS) are modelled. In the RS, the continuation of current trends is assumed, with energy efficiency improvements for the respective industries, but no additional sector-specific decarbonization measures. The TS assumes an ambitious decarbonization scenario, in which energy carrier substitution, circular economy measures, material efficiency improvements, and process route changes are accounted for as decarbonization measures. Additional information on the methodology and results can be found in the accompanying publication [73].

4.3.1 Results

The model results indicate that the future industrial demand response potentials in Europe are substantial, but also strongly scenario-dependent. Overall, average hourly positive (load reduction) and negative (load increase) demand response potentials are estimated at roughly 17 GW and 8 GW, respectively, in 2020, rising to about 29 GW and 11 GW in 2050 under the target scenario. In the reference scenario, by contrast, positive demand response potential reaches only around 13 GW and negative demand response potential around 6 GW in 2050, amounting to less than half of the flexibility available

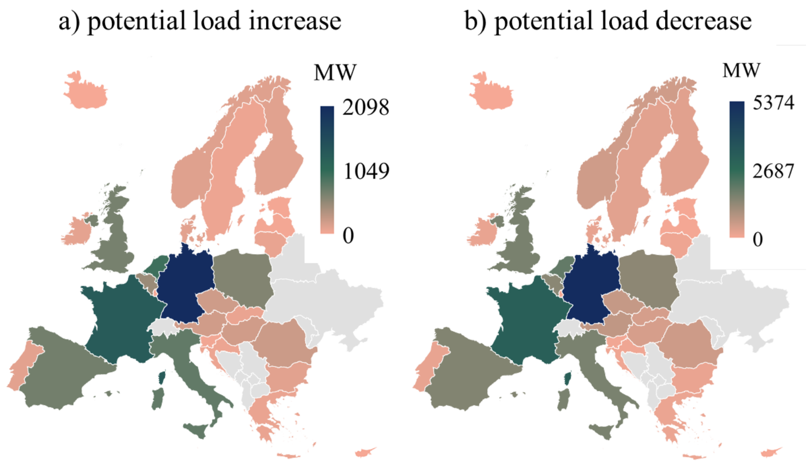

FIGURE 4.15. *Annual average a) load increase and b) load decrease potentials of the target scenario in 2030. Published in [73].*

in the target scenario. Furthermore, the load reduction potential of the target scenario in 2050 corresponds to around two-thirds of today's European pumped hydro capacity, underscoring the potential strategic role of industrial demand response [106]. Germany exhibits the highest demand response potentials, followed by France, reflecting their already substantial energy-intensive industrial production capacities, as Figure 4.15 for 2030 exemplarily.

At the process level, ambitious decarbonisation substantially reshapes the demand response landscape, as illustrated in Figure 4.16: ammonia electrolysis, meat, and milk production emerge as the processes with the highest future load flexibility potentials, with secondary steel production via the electric arc furnace adding considerable load-decrease potential. Food processing (meat, milk, baked goods) offers considerable sheddable and shiftable loads but faces comparatively high variable costs for shedding, suggesting a stronger suitability for load shifting rather than outright shedding. In some existing processes, such as paper or conventional glass production, the flexibility potential declines with efficiency gains or process substitution.

The analysis highlights that deep industrial decarbonization can increase overall demand response potential, but in a highly heterogeneous manner across processes and

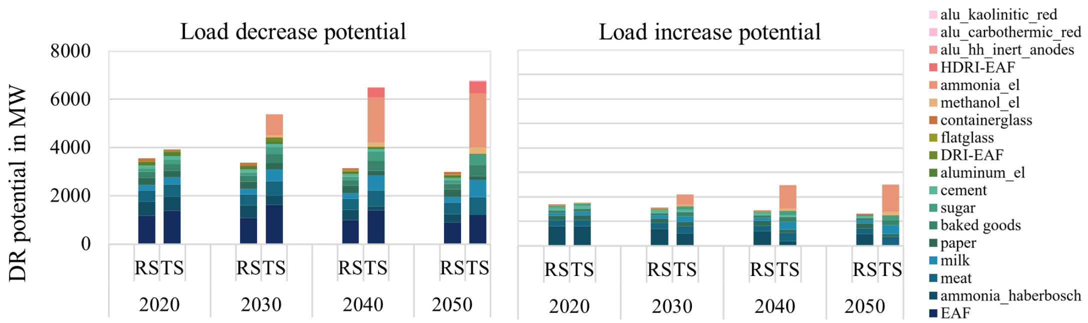

FIGURE 4.16. *Annual average load increase and decrease potentials by process and scenario (RS: reference scenario, TS: target scenario). Published in [73].*

countries. At the same time, the study acknowledges limitations related to parameter uncertainty, the use of synthetic rather than metered load profiles, and the omission of detailed process-specific operational constraints, motivating future work to validate these potentials and examine their economic value in electricity market models.

4.3.2 Discussion

Understanding how much flexibility energy-intensive industry can realistically provide is crucial for system planning under ambitious decarbonization pathways. Eighteen processes were evaluated with respect to their hourly load shifting and load shedding capabilities, offering detailed insights into how industrial flexibility potentials may evolve in the future [73]. At the aggregated European level, the average hourly DR potential for load reduction amounts to approximately 16-17 GW in 2020 and increases to 13-29 GW in 2050 across the reference and target scenarios. In parallel, load increase potentials range from about 7-8 GW in 2020 to 6-11 GW in 2050. These results highlight the growing strategic relevance of industrial flexibility in a deeply decarbonized energy system, particularly in conjunction with increasing process electrification and the large-scale deployment of green hydrogen. The highest future load increase potentials are identified in ammonia electrolysis as well as in meat and milk production, while load shedding potentials are primarily associated with ammonia electrolysis, electric arc furnaces, and food processing.

From an economic perspective, however, load shedding, especially in the food sector, is characterized by comparatively high variable costs, suggesting that these processes are generally better suited for load shifting rather than absolute load reduction. Moreover, several processes that appear attractive from a flexibility perspective in the near term, such as cement production or direct reduced iron with electric arc furnaces, may lose relevance in the long term due to fundamental changes in production routes and energy carrier substitution. In the case of cement, this points to the need for further research on future-oriented production pathways such as belite cement and autoclaved aerated concrete. Finally, the study reveals pronounced regional differences in flexibility potentials across Europe, closely reflecting the spatial distribution of energy-intensive industries. Accordingly, Germany, characterized by the highest industrial electricity demand, also exhibits the largest industrial flexibility potential in the European context.

The results should be interpreted as an initial assessment of industrial flexibility potentials. Load profiles are based on process-specific literature values and synthesized open-source data, as plant-level metered data were unavailable. The analysis does not consider operational constraints that may limit demand-response provision, such as restrictions on intervention timing or frequency, nor does it model explicit market participation through bidding strategies. Consequently, the estimated flexibility potentials represent technical rather than economic potentials. Future work could address these limitations by incorporating process-specific operational constraints and linking industrial flexibility to an agent-based electricity market model.

5 Conclusions

This project set out to advance the understanding of industrial transformation pathways in Europe through a combination of site-specific modeling, technology diffusion analysis, and industrial flexibility assessments. The work was guided by two overarching research questions: how the technology mix in European industry may evolve under alternative long-term decarbonization pathways, and how industrial electrification could affect future flexibility potentials and their deployment. To address these questions, the project developed and applied two complementary open-source modeling frameworks, FORECAST-Sites Extended and iSTEDS, which were accompanied by scientific publications and made publicly available to support transparent and reproducible research.

The three exemplary case studies presented in this report demonstrate that industrial decarbonization is neither uniform nor governed by a single technology pathway. The site-specific analyses using FORECAST-Sites Extended showed that technology adoption depends strongly on local conditions, particularly asset vintages, reinvestment timing, infrastructure availability, and sector-specific technology costs. While hydrogen emerges as a central decarbonization option in several industries, its adoption varies considerably across sectors and sites, highlighting the importance of both infrastructure development and technology competitiveness.

The carbon-capture case study showed that no single mitigation technology is universally applicable across industry. Instead, the role of carbon capture depends on the nature of industrial emissions and the availability of alternative low-carbon production routes. In sectors with unavoidable process emissions, carbon capture appears to be a key long-term mitigation strategy, whereas in other sectors it is likely to serve a transitional role alongside broader technological change.

The flexibility assessment demonstrated that industrial electrification not only increases electricity demand but also creates new opportunities for demand-side flexibility. Significant flexibility potentials were identified across a range of industrial processes, suggesting that industry may play an increasingly important role in supporting future electricity systems with high shares of variable renewable generation.

Taken together, several overarching patterns emerge. First, industrial decarbonization is highly heterogeneous, with transition pathways differing substantially across sectors, technologies, and locations. Second, infrastructure availability—particularly access to hydrogen networks—can be as important as technology costs in determining investment outcomes. Third, the timing of asset replacement and reinvestment decisions plays a crucial role in shaping long-term technology diffusion. Finally, the transition of industry cannot be viewed in isolation from the wider energy system: technology adoption, infrastructure requirements, carbon mitigation strategies, and flexibility provision are closely interconnected and must be considered jointly.

The outlook for this work lies in the continued development of the underlying databases and modeling frameworks through contributions from the wider research community. In addition, further integration of industrial transformation models with energy system and electricity market models offers considerable potential to improve the representation of interactions between industrial decarbonization, infrastructure development, and future energy system operation.

Appendix: List of scientific outputs

Conference and journal publications:

- **Britto, A.**, Gröning, L., **Scharnhorst, L.**, Kleinebrahm, M., & Fichtner, W. (2026). *Future Hydrogen Demand in Europe's Steel and Chemical Sectors: A Site-Specific Assessment*. Submitted to *Energy Conversion and Management*.
- Bergler, L., **Scharnhorst, L.**, **Britto, A.**, Kleinebrahm, M., & Fichtner, W. (2026). *A logit-based technology diffusion model on carbon capture diffusion in Europe's hard-to-abate industry*. In *Proceedings of the 22nd International Conference on the European Energy Market (EEM 2026)*, Trondheim, Norway. (Full paper accepted; DOI pending).
- **Scharnhorst, L.**, Xie, X., Kleinebrahm, M., & Fichtner, W. (2024). *Techno-economic analysis of future process-specific demand response in European industries*. In *Proceedings of the 20th International Conference on the European Energy Market (EEM 2024)*, Istanbul, Turkey. DOI: 10.1109/EEM60825.2024.10608488.
- **Scharnhorst, L.**, Sloot, D., Lehmann, N., Ardone, A., & Fichtner, W. (2024). *Barriers to demand response in the commercial and industrial sectors: An empirical investigation. Renewable and Sustainable Energy Reviews, 190*, 114067. DOI: 10.1016/j.rser.2023.114067.

Models & datasets:

- Forecast-Sites Extended contributors (2026). *forecast-sites-ext (Version/commit a487017)*. KIT GitLab. https://gitlab.kit.edu/kit/iip/opensource/forecast-sites-ext
- Bergler, **L., Scharnhorst, L., Britto, A.**, Kleinebrahm, M., Wolf, F. (2026). *Future carbon capture technology diffusion in Europe's hard-to-abate industries*. Zenodo, 4 March 2026. DOI: 10.5281/zenodo.18863062.

Doctoral theses:

- **Scharnhorst, L.** (2026). *Behavioral and Structural Drivers of Energy Demand Flexibility*. Doctoral dissertation, Karlsruhe Institute of Technology. (DOI pending).
- **Britto, A.** (2026). *Optimal Consumer Adoption of Energy Efficiency*. Doctoral dissertation, Karlsruhe Institute of Technology. DOI: 10.5445/IR/1000192844.

Student theses:

- Bergler, L. (2026). *Beyond One-Technology-Fits-All: A Discrete-Choice Model on Carbon Capture Diffusion in Europe's Hard-to-Abate Industry*. Bachelor's thesis, Karlsruhe Institute of Technology.
- Gröning, L. (2026). *Modeling Hydrogen Pathways for the European Chemical Industry*. Bachelor's thesis, Karlsruhe Institute of Technology.
- Tröndle, N. (2025). *Open-Science-Based Modeling of Technology Diffusion in Europe's Energy-Intensive Industry by 2050*. Bachelor's thesis, Karlsruhe Institute of Technology.

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