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Modeling cost-minimal transformation pathways for three energy-intensive industrial sectors: an Austrian case study by 2040

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Institute of Energy Systems and Electrical Drives

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Abstract

The industrial sector is one of the most significant drivers of global CO_2 emissions, accounting for a quarter of global greenhouse gases. In fact, 60 % of the sector's energy demand originates from fossil fuels, mainly caused by high-temperature process heating applications that rely on energy carriers with a high energy density. Decarbonizing these industrial processes is, therefore, challenging but absolutely essential for a carbon-neutral energy system. This work aims to identify sustainable technology options for three energy-intensive industry sectors and to find cost-minimal transformation pathways to implement these technologies until 2040. Those transformation pathways are calculated for two scenarios, determined by the availability and costs of the energy carriers used in the industrial production sites. The analyzed industrial sectors represent Austria's Iron & Steel, Pulp & Paper and Cement industries and their respective industrial locations, considering their spatial distribution. A mixed integer linear program is proposed as an optimization model with the objective of minimizing the overall system costs. The system's costs are determined by the investments into transition technologies and operational costs, while the implementation of transition technologies can reduce CO_2 emissions and energy demand and, therefore, their operational costs. The calculated results show that industrial decarbonization can be achieved by investing in energy efficiency improvements, carbon capture technologies, and replacement of applications using fossil fuels. Renewable gases or hydrogen are suitable to replace fossil fuels for high-temperature heating applications and will be used in the Iron & Steel sector. Industrial heat pumps can generate low-temperature steam or heat and help to decarbonize the Pulp & Paper industry in the results. At the same time, carbon capture is necessary in some hard-to-abate sectors, especially in cement-producing sites, to achieve carbon neutrality. The projected transformation pathways indicate that the energy carrier costs are by far the most significant cost term in the model's results. Therefore, the cost-efficient availability of sustainable energy carriers is the main lever for deciding to invest in decarbonization options. Focusing on an Austrian or EU-wide supply and distribution of renewable energy carriers is crucial for a competitive and carbon-neutral industrial energy system.

Kurzfassung

Der Industriesektor ist mit rund einem Viertel der weltweiten CO_2 Emissionen einer der Hauptverursacher des Klimawandels. Die Emissionen stammen größtenteils aus der Verbrennung fossiler Brennstoffe, die zur Erzeugung von Hochtemperatur-Prozesswärme benötigt werden. Da diese Hochtemperaturanwendungen auf Energieträger mit hoher Energiedichte angewiesen sind, ist die Dekarbonisierung industrieller Prozesse zwar eine Herausforderung, sie ist für ein klimaneutrales Energiesystem aber unumgänglich. Das Ziel dieser Arbeit besteht darin, nachhaltige Technologieoptionen für drei energieintensive Industriesektoren zu identifizieren und kostenminimale Transformationspfade bis 2040 zu finden. Diese Transformationspfade werden für zwei Szenarien berechnet, die durch die Verfügbarkeit und die Kosten der verwendeten Energieträger bestimmt werden. Die untersuchten Produktionsstätten gehören zu Österreichs Stahl-, Papier- und Zementindustrie. Es wird ein gemischt-ganzzahliges lineares Optimierungsmodell vorgeschlagen, dessen Ziel es ist, die Gesamtsystemkosten zu minimieren. Die Kosten setzen sich aus den Investitionskosten und den Betriebskosten zusammen. Die Installation von nachhaltigen Technologien oder die Optimierung der Prozesse kann die CO_2 Emissionen und den Energiebedarf reduzieren und somit wiederum die Betriebskosten senken. Als erfolgsversprechende Technologien erweisen sich Energieffizienzsteigerungen, Kohlenstoffabscheidung, Elektrifizierung von Prozesswärmeerzeugung und Ersatz fossiler Brennstoffe durch erneuerbares Methan oder Wasserstoff. Industrielle Wärmepumpen können zur Erzeugung von Niedertemperaturdampf in Papierfabriken eingesetzt werden und erneurbarer Methan oder Wasserstoff zur Stahlherstellung. Kohlenstoffabscheidung ist in manchen Bereichen der Industrie wie der Zementindustrie notwendig, um eine Dekarbonisierung zu erreichen. Die projizierten Umwandlungspfade zeigen, dass die Kosten für Energieträger bei den Modellergebnissen den weitaus größten Kostenanteil ausmachen. Die kosteneffiziente Verfügbarkeit von nachhaltigen Energieträgern ist somit der wichtigste Faktor bei der Entscheidung, in Dekarbonisierungsoptionen zu investieren. Die Versorgung und Verteilung erneuerbarer Energieträger in Österreich und der EU ist entscheidend für ein wettbewerbsfähiges und klimaneutrales industrielles Energiesystem.

Contents

Abbreviations

GHG	Green House Gas
MILP	Mixed Integer Linear Program
TRL	Technology Readiness Level
IS	Iron and Steel
PP	Paper and Pulp
NMM	Non-Metallic Minerals
SEC	Specific Energy Consumption
EEI	Energy Efficiency Improvement
ELEC	Electrification
FS	Fuel Switch
CCS/CCUS	Carbon Capture and Storage / Carbon Capture and Utilization
BF	Blast Furnace
BOF	Basic Oxygen Furnace
EAF	Electric Arc Furnace
DRI	Direct Reduction Iron
CHP	Combined Heat and Power
NG	Natural Gas
GG	Green Gases
LAU	Local Administrative Unit

1 Introduction

1.1 Motivation and background

The industry was responsible for a quarter of the global GHG emissions in 2022, and the emissions in the sector have increased by 70 % since 2000 (IEA, 2022). This means that finding ways to mitigate emissions in the industry needs to be a cornerstone for the future energy system to reach the European GHG reduction goal of 55 %. The European Union (EU) officially states, regarding the industry:

> "Industry is the backbone of the European economy. Europe's global competitive advantage in high value-added products and services translates to more than 20 % of the EU's total value-added, with industry directly providing 35 million jobs. Competitiveness is therefore at the heart of the Commission's agenda, and as we stand on the brink of a new industrial revolution, we are committed to supporting the digital and green transformation of EU industry."

In March 2023, the EU released the Net-Zero Industry Act to strengthen the implementation of net-zero technologies in Europe's manufacturing economies (EU, 2023). This is, besides the Critical Raw Materials Act and the reform of the electricity market, part of the EU's Green Deal Industrial Plan, aiming to support climate neutrality and competitiveness of Europe's industry. The Net-Zero Industry Act aims to achieve a green transition and to replace the reliance on Russian fossil fuels. Besides the EU-wide plan for a green industry, the EU's member states also have national plans to achieve climate neutrality. In Austria, the industry is a central part of these climate plans and, therefore, a key lever for the country's decarbonization targets.

Austria has the goal of full decarbonization of the energy system until 2040. Austria's industry, together with the power sector accounting for 37 % of Austria's GHG emissions, has to be fundamentally transformed to achieve this decarbonization (Diendorfer et al., 2021). The industry in Austria is responsible for an added value of 34 % of the economy. It is a significant provider of employment, so the emigration of industrial companies is no viable solution to reach decarbonization targets. A cost-efficient sustainable transformation of the industrial energy system and its used energy carriers is an essential part of the pathways to decarbonization. The availability of energy carriers used in the industry along this way and in the future energy system takes a vital role.

The demand for fossil fuels in Austria's industry is about two-thirds of the energy demand (StatistikAustria, 2022). Therefore, the accessibility to fossil fuels like natural gas or substitutes for fossil fuels like hydrogen or renewable methane is critical for implementing a technological shift in the industry.

1.2 Two research questions

Against this background, the main goal of this thesis is to answer the following two research questions:

- How are the cost-minimal transformation pathways for the three selected energy-intensive industrial sectors (Iron & Steel, Pulp & Paper, Cement) in Austria by 2040 defined from a techno-economic perspective?
- To what extent are these cost-minimal industrial transformation pathways sensitive to the availability of the different energy network infrastructures, especially in view of their expected sustainable transition?

The first research question relates to assessing transformation pathways for the industry. The installment of sustainable technologies for the industrial processes in different industrial locations in the sectors and the year of installation until 2040 is the central part of these transformation pathways. Also, part of the transformation is the demand for energy carriers in the respective sites, which changes in various ways through the decarbonization options. Therefore, the development of the demand for energy carriers is a crucial part of research question one. As the objective of the optimization is cost minimization, the occurring costs have to be analyzed, too. In other words, a portfolio optimization is conducted in order to answer the first research question.

The second research question pertains to the regional aspect of this work. Parameters regarding the availability of the network infrastructure or the energy carrier need to be identified to quantify their impact on the results of the optimization. Parameters to answer this question are, for instance, the amount of a renewable energy carrier available in a year, the cost of this energy carrier, or the access of an industrial site to an infrastructure providing an energy carrier. To fulfill this task, not only the current state of the network infrastructure is essential, but also the development until the end of the time horizon (e.g. repurposing of natural gas pipelines for transporting green hydrogen).

1.3 Applied method

To answer those research questions, a mathematical optimization model is introduced, which calculates transformation pathways for the industry in Austria, consisting of the implementation of technologies on an annual basis in the different industrial sites that promote carbon neutrality. Those pathways are worked out for two scenarios, defined by the available energy network infrastructure. The optimization approach consists of a mixed integer linear program (MILP) that calculates cost-minimal investment decisions and turns them into sustainable technology options for the industry. The binary variables necessary for a MILP are essential because the decision to install some technologies is non-linear. For example, a high-temperature furnace can be either replaced with a less carbon-intensive option or not, making the decision binary. This model is implemented in Python, using the Pyomo[1] package and solved with the Gurobi[2] solver. The cost minimization includes investment costs, energy carrier costs, and costs for GHG emissions. Besides other parameters, the model considers alterations in the industrial process due to the installment of technologies for decarbonization, annual production rate, specific CO_2 emissions, and specific demand.

1.4 Structure of the thesis

This work is organized as follows. Chapter 2 provides an overview of the industry in Austria, including its emissions, energy demand, and decarbonization options. The gas network development and industry modeling in current energy system models are explained before their contribution to this topic is outlined. Chapter 3 elaborates on the applied methodological approach and its mathematical formulation. Also, the industrial sectors analyzed in the optimization are further explained, and the technological decarbonization options for these sectors are introduced. Chapter 4 states the goals of the scenario development and the two defined scenarios and their parameters. Chapter 5 contains the results. Here, the calculated transformation pathways, the energy demand, the costs, and the CO_2 mitigation in the scenarios are explained. An additional case is analyzed, and the scenarios are compared. Chapter 6 concludes the results of this work and discusses the key findings.

[1] http://www.pyomo.org/
[2] https://www.gurobi.com/

2 State of the art and progress beyond

This chapter summarizes the current state of knowledge in the literature about the role of industry in the energy system and prospected options for decarbonization. It provides an overview of the Austrian industry and its unique characteristics, as well as possible decarbonization options and types of transition technologies, and outlines transformation pathways for the Austrian industry in the literature. A brief description of the Austrian gas network development and the challenges associated with incorporating the industry into large-scale energy system models are given. Finally, the contribution of this thesis to the modeling of industrial transformation pathways is explained.

2.1 The Austrian industry sector and its transformation pathways

The industry is responsible for 30 % for Austria's final energy demand (StatistikAustria, 2022) and 35 % or 112 TWh total energy consumption (Sejkora et al., 2018). Table 2.1 shows the final energy demand in Austria in the different economic sectors transport, industry, residential, commercial, and agriculture, where the industry consumes 88.7 TWh.
In 2021, 77.5 Mt CO_2 were emitted in Austria. The industry holds by far the major part with 26 Mt CO_2 , and 20.2 Mt CO_2 from that were inside the European Emission Trading System (EU-ETS). Industrial emissions have risen by 20 % since 1990, with one of the main drivers for this increase being the Iron and Steel (IS) sector. (Umweltbundesamt, 2023b)

Transport	Industry	Residential	Commercial	Agricultural
94.6 TWh	88.7 TWh	77.3 TWh	29.4 TWh	6.1 TWh

Table 2.1: Final energy consumption in Austria by sector in 2022 (StatistikAustria, 2022)

The data acquisition for the industry is inconsistent in different sources because the term "industry" in some publications refers only to the manufacturing economic sectors, and sometimes it also includes mining and quarrying or the power sector (Napp et al., 2014). Therefore, it is important to define the term industry for this thesis. The EU mostly uses the International Standard Industrial Classification system (ISIC) from the United Nations (UN, 2008), which breaks down different types of economic activities. Out of this classification system, three main sections are used in this thesis: Section B includes mining and quarrying, section C covers all manufacturing sectors, and section F covers construction. 13 industrial subsectors are then identified for this work[1]: Iron and Steel; Pulp and Paper; Non Metallic Minerals; Chemical and Petrochemical; Non-Ferrous Metals; Transport Equipment; Machinery; Mining and Quarrying; Food, Tobacco and Beverages; Wood and Wood Products; Construction; Textiles and Leather; Non Specified Industry. The first five sectors are specified as energy-intensive industrial sectors and account for more than two-thirds of industrial energy consumption and emissions (IEA, 2021).

The demand for fossil fuels in the industry is very high, almost 60 % of the final energy demand in Austria stems from fossil fuels (StatistikAustria, 2022). Figure 2.1 shows the consumption of different energy carriers in the industry, whereas coal consumption includes non-energy use in the coke ovens of the steel production. Natural Gas (NG) is with 30 % the most consumed energy carrier in the industry, followed by coal and electricity, both with about 27 %. 16 % of final energy consumption are renewables and biofuels like biomass. District heat, oil, and non-renewable waste make up for smaller shares of energy demand in the industry.

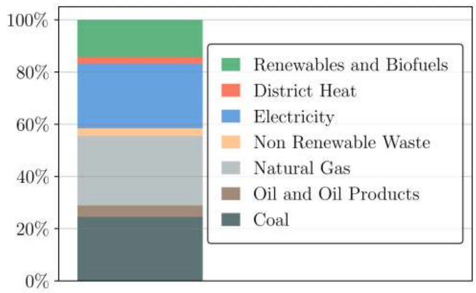

Figure 2.1: Share of energy carrier on industrial final energy demand in Austria (StatistikAustria, 2022)

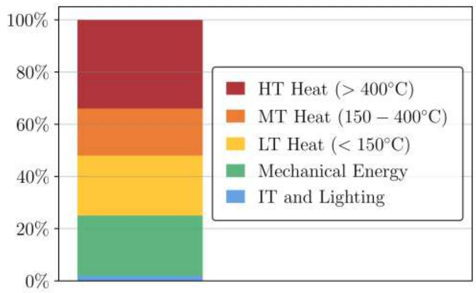

Figure 2.2: Share of useful energy and temperature level of process heat in industrial energy demand, data from (Rohde, 2013) and (Saygin et al., 2014)

Figure 2.2 illustrates the useful energy in the industry, where heat processes make up for 75 % of useful energy, mechanical energy uses 23 % of the energy demand and

[1]A further breakdown for the analysis will be made in section 3.2

other applications like IT and lighting use about 2 % (Rohde, 2013). Of the heating generation applications, 32 % are used for low-temperature processes below 150 °C like low-temperature steam generation or space heating, 23 % is used for medium temperature heat processes between 150 °C and 400 °C like drying processes and 45 % are used for high-temperature heating processes above 400 °C like smelting in high-temperature furnaces (Saygin et al., 2014).
More than half of the industry's energy demand is used to generate medium- to high-temperature heat, which today is mostly provided by fossil fuels, which therefore have a high share of the energy demand in the industry. Those heating processes are making the industry, especially the energy-intensive industry, challenging to decarbonize because generating these temperatures through an alternative source like electricity is yet to be practical on a larger scale (IEA, 2021). Applications using less carbon-intensive energy carriers like hydrogen are still in the early stages of development but are necessary for a deep decarbonization of the industrial energy system.

2.1.1 Sustainable energy alternatives for energy-intensive industries

Low-carbon technologies are crucial in leading to deep decarbonization of the industrial sector, especially for the energy-intensive industry (Chan, Petithuguenin, et al., 2019). These technologies are here referred to as transition technologies and can be divided into five decarbonization options, so-called pillars: Energy Efficiency Improvements (EEI) using best practice technologies in the processes; Fuel Switch (FS) replacing fossil fuels with a less carbon-intensive technology; Electrification (ELEC) of parts of the heating generation processes; Carbon Capture and Storage (CCS) or Carbon Capture Utilization and Storage (CCUS); Circular Economy (Mobarakeh and Kienberger, 2022). In the past, the main focus of transition technologies was on EEI, which helps with short- to medium-term decarbonization. For long-term decarbonization of the industry, a combination of more different pillars must be considered (Nurdiawati and Urban, 2021). However, because of the variety of industrial subsectors and product palettes, a large amount of transition technologies are only suitable for specific applications and subsectors. The differentiation depends on several factors, whereas the temperature levels for heat production and mechanical applications have already been discussed, another significant distinction is the source of CO_2 emissions. Fuel-related emissions stem directly from fossil fuel combustion in industrial furnaces or to produce steam. Process-related emissions are a part of the industrial process for some subsectors like IS and cement and can also occur from non-energy use of fossil fuels, like coke as a reducing agent in steel production (Mobarakeh and Kienberger, 2022).
The identification of transition technologies in the analyzed subsectors is a central part of this work and is further discussed in section 3.2. However, examples for some transition technologies in the different pillars and an explanation for the pillars, derived

from (Schützenhofer et al., 2024) and (Mobarakeh and Kienberger, 2022), are introduced here:

- **Energy Efficiency Improvement**
  Improve the energy efficiency of the various processes through different technologies, reduce energy demand, and consequently, reduce emissions.
  - Direct waste heat utilization for space heat and low-temperature process heat
  - Improve the efficiency of mechanical drives
- **Fuel Switch**
  Replacing fossil fuels with less carbon-intensive energy carriers like hydrogen, green gases, or biogas. Usually necessary for high-temperature heating applications like industrial furnaces or non-energy use.
  - Switch to medium-temperature or high-temperature steam generation powered by biomass boilers
  - Switch from coke-powered steel production to direct reduction with green gases or hydrogen and electric arc furnace, reducing both fuel-related and process-related emissions
- **Electrification**
  Electrification of process heat demand or steam generation, at the moment, is commercially available for applications up to 400 °C
  - Heat pumps for using industrial waste heat to produce low-temperature process heat or space heating
  - Advanced electric boilers to generate medium-temperature process heat or steam
- **Carbon Capture and Storage**
  Help to decarbonize hard-to-abate sectors and mitigate emissions occurring in the process.
- **Circular Economy**
  Increasing the efficiency of material use is crucial for the decarbonization of the industry. Increase the rate of recycling to reduce the need for raw material production like pulping, reducing iron ore or recycling of aluminum.

Besides the pillars and the respective branches, more parameters are important for the transition technologies. One important aspect besides the branch is the specific application or part of the process on which the transition technology can be used. Another major parameter is the technology readiness level (TRL), which gives information about the market maturity of a technology. The scale goes from TRL 1 to TRL 9, where TRL 1 means, that the basic principle is observed and reported, TRL 2-4 means that the technology or components of it have been simulated or built and validated in laboratories, TRL 5-7 mean that a prototype has been made and tested and TRL 8-9 mean that the technology has reached its market maturity and can then be commercially available (Mankins, 1995).

2.1.2 Overview of transformation scenarios for industry sectors

There are several transformation pathways for the industrial energy system outlined globally, like in "World Energy Outlook 2023" (P. IEA, 2023) or on a national scale for Austria, mostly from publications from the "New Energy For Industry" (NEFI) project like in the final report "transform.industry" (Schützenhofer et al., 2024).

The World Energy Outlook outlines three different scenarios until 2050: the *Stated Policies Scenario* (*STEPS*) provides an outlook based on the latest policy settings, the *Announced Pledges Scenario* (*APS*) expects all announced national climate targets to be reached, and the *Net Zero Emissions* (*NEZ*) scenario is working to reach the 1.5 °C goal. In the STEPS, overall energy demand increases the most, while the demand in the other two sectors does not change significantly until 2050. In the , NZE scenario, coal and NG consumption is almost fully replaced by electricity or bioenergy, with an electricity demand increase mainly occurring in direct process heat generation or hydrogen production in electrolyzers. Electricity is the most important energy carrier for the industry's global decarbonization pathways. Its demand increases in all scenarios and will be especially used for direct process heating and hydrogen production. Another important measure in all scenarios is promoting material efficiency and increasing the recycling rate.

In the "transform.industry" report, four scenarios until 2040 are described to maximize either innovation in the industrial sites, secondary production with more recycling, the use of renewable energy carriers, or sector coupling between industry and other sectors, industrial subsectors, or industrial sites. The energy demand in all scenarios increases by 15 % to 24 %, and the main energy sources in 2040 will be electricity and renewable gases, together amounting to about 70 % of the energy demand across all scenarios. Some technological transformations, identified here as no-regret options, are proven to be economically viable in all scenarios. The direct or indirect use of industrial waste heat, biomass boilers, CCS, and replacing fossil fuels for non-energy use in the IS and the chemical sector are some of those no-regret options. The report also recommends actions for policymakers to promote industrial decarbonization: Because of the high investment costs, funding for innovative technologies could reduce risks, especially for smaller businesses; Promoting the generation and distribution of renewable energy carriers like electricity, hydrogen, or green gases is crucial for the transformation;

Increase joint procurement of materials to promote recycling and secondary production processes.

2.1.3 Austria's gas network until 2040

To answer the second research question and consider the energy network infrastructure in this thesis, the gas network development is crucial because the gas network will include both NG and renewable gases or hydrogen. The information regarding the current and future gas network infrastructure is derived from a study from frontier economics and TU Wien, called "Rolle der Gasinfrastruktur in einem klimaneutralen Österreich" (BMK, 2023).
This study aims to analyze the future role of the gas infrastructure in a climate-neutral Austrian energy system. The transmission, high- and mid-pressure levels are analyzed for different assumptions regarding the demand with the target of a climate-neutral gas demand in 2040. Four scenarios are outlined varying the following dimensions: Degree of electrification; Sectoral distribution of gas demand; Decentralism of renewable gases and hydrogen. The four scenarios are called: *Electrification* with a high degree of electricity in the system and a reduced gas demand; *Green Gases* with a higher penetration of hydrogen and less electrification, also a centralized approach; *Green Methane* also with little electrification but more gas demand, but here the focus lies on renewable gases instead of hydrogen; *Decentralized Green Gases* with a regionally distributed gas demand and gas generation.
The methane network is not very different in 2030 than in 2020 in all scenarios, after 2035 until 2040, the gas infrastructure in the scenarios differs significantly, with a methane network reduction between -26 % and -39 %. The methane demand will be increasingly driven by biomethane generation and the ratio of centralization of generation and consumption of biomethane. The hydrogen network will be very centralized by 2030 with concentrated big consumers. An increasing number of hydrogen consumers and their spatial distribution led to a growing hydrogen network in all scenarios until 2040, with the repurposing of some methane pipelines into hydrogen pipelines.

2.2 Modeling the industry sector in energy system models and related challenges

Most large-scale energy system models consider the industry as aggregated large consumers, which is insufficient for representing the sector's heterogeneity, especially when finding options to decarbonize the sector. Relevant details such as the process heat generation, type of fuel consumption, and spatial or temporal resolution are often

neglected (Wiese and Baldini, 2018). ”PRIMES”, a partial equilibrium optimization model for the EU, considers the industry as nine subsectors in a modular system to project fuel, electricity, or steam demand. This model focuses on policy analysis, so technological shifts in the industry are attempted to be considered. However, given the sector's complexity, this is a difficult task for such a large model (Mantzos and Capros, 1999).
However, some models try to embed the industrial subsectors, their processes, and the decarbonization options separately in an energy system model like the model ”FORECAST”. Here, the different process steps and specific fuel demand are considered, and the improvement of the energy demand through the implementation of transition technologies is calculated. The results are given as time series and include information about the energy demand, GHG emissions, costs, and technologies and can be further processed (Fleiter et al., 2018). The energy network infrastructure is not considered in this model.

2.3 Novelties and own contribution

The contribution of this work and the novelties to this topic are in line with the research questions. They can be separated into the methodological aspects, regional aspects, and the analyzed data.

Bottom-up modeling of industrial transformation pathways in energy system models

A detailed consideration of the industry in energy system models is a crucial cornerstone of analyzing a climate-neutral future energy system. Therefore, in this work, a techno-economic bottom-up analysis is carried out to find the cost-minimal transformation pathways for the industry. These transformation pathways are defined in the form of a technology roll-out in every industrial site. Parameters determining the input of the model, like energy carrier prices, annual production rate, or amount of an energy carrier available, are passed to the model top-down. The contribution to fulfilling this task is to develop the optimization model that carries out the calculation and the identification of decarbonization options for the industry and the respective industrial sites.

Consideration of the gas network on a regional level

The consideration of the gas network on a regional level is a further novelty of this approach. Although some studies include the energy carrier supply, the effects of energy carrier availability per industrial location on the transformation are yet to be explored. In this work, the energy network for NG, renewable gases, and hydrogen are represented until 2040 to analyze the effects of the grid connection of industrial consumers.

Austrian case study

Although detailed research into industrial transformation in Austria already exists, considering Austria's spatially distributed industrial landscape is a novelty here. Detailed information about the different industrial sites, their annual production rate, and their location are taken into account, as well as the energy network infrastructure in Austria. Further parameters like fuel prices or subsidies are integrated and can be expanded to raise conclusions about policy decisions.

3 Methodology

The following section introduces the applied modeling approach for the optimization. The model's general idea is presented first, followed by a selection of the analyzed energy-intensive industry sectors, their structure and energy demand, and their decarbonization opportunities considered in this work. Finally, the mathematical formulation of the model is presented.

3.1 Introduction to the method

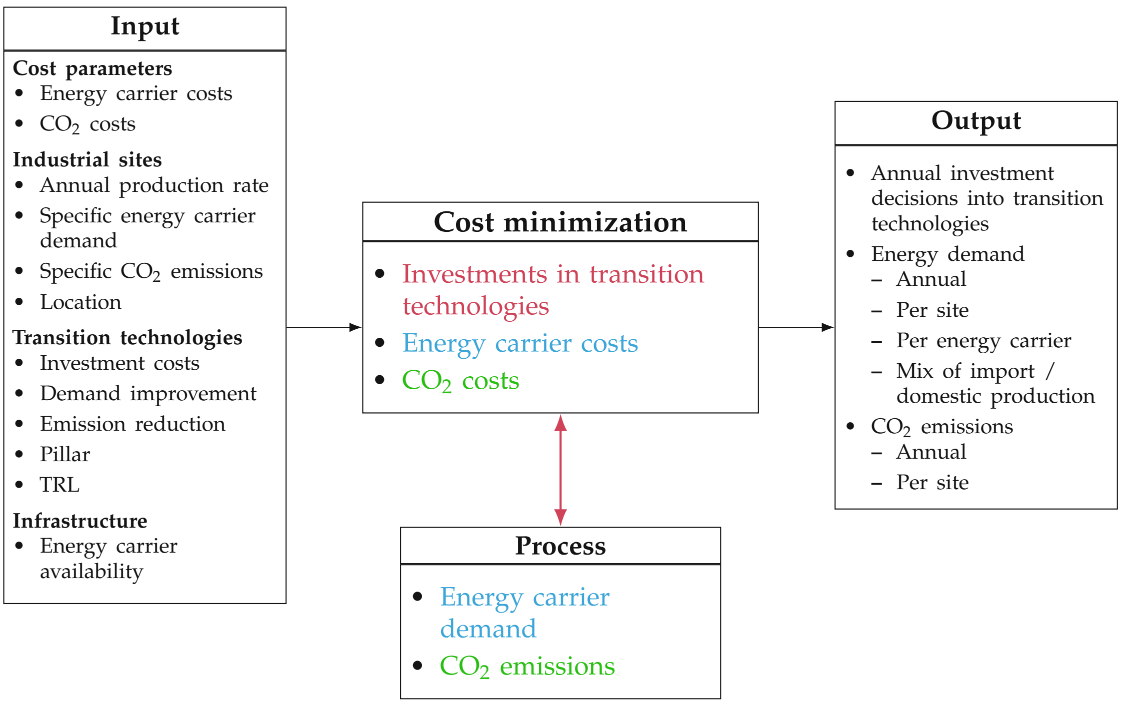

Figure 3.1: Flow-chart of the modeling approach

As the fundamental nature of the industry's transformation is a technological adaption, the principal concept of the method consists of installation decisions into transition technologies in the industrial sites of the selected sectors in Austria's industry. These transition technologies can be installed in various parts of the process or replace components of an industrial site. For instance, a technology that improves energy efficiency can reduce energy demand and greenhouse gas emissions. Similarly, switching to electrified process-heat generation can increase electricity demand but, in turn, decrease the need for fossil fuels, which again reduces carbon emissions.

This model combines a top-down and a bottom-up approach where investment decisions at a local level are made based on operational costs and energy carrier availability given top-down by the system. The local investment decisions represent the bottom-up modeling of the transformation pathways. The model's input parameters, as stated in figure 3.1, relate to costs, industrial sites, transition technologies, and the energy network infrastructure. The input data for the network infrastructure can limit either the availability of an energy carrier at a site or the maximum available capacity of an energy carrier in the overall system.
The objective of the calculation is to minimize the overall system costs, which consist of investment costs into the transition technologies, the costs for energy carriers, and the costs for emitting CO_2 . The figure 3.1 shows that the installation of technologies (illustrated with the red arrow) increases investment costs but also impacts the process and its efficiency and demand, resulting in reduced or at least altered payments for energy carriers and carbon emissions. The optimization results in transformation pathways for each industrial site. These pathways involve the installment of transition technologies that lead to a change in energy carrier demand and a reduction in CO_2 emissions. The energy demand in the system also depends on the amount of domestically produced energy carriers available.

3.2 Three key sectors of the energy-intensive industry and their decarbonization options

In this section, a selection of three energy-intensive industrial sectors for the analysis and an explanation for this choice are given. Furthermore, these key sectors and their current parameters and entities are introduced, followed by specific decarbonization options for these sectors. Unless otherwise stated, the information in this section is derived from (Mobarakeh and Kienberger, 2022).
The given overview of these sectors includes their principal processes, energy carrier demand, and CO_2 emissions. Additionally, the industrial sites that were examined are presented.
The decarbonization options include the transition technologies available in the analyzed industrial sectors and considered in this work's optimization. The data focuses

on the potential for decarbonization, taking into account the change in the emission factor and specific energy demand of the process based on the installation of the technology. Generally, these transition technologies are applied in different stages to reduce process-related emissions, fuel-related emissions for high-temperature applications above 400 °C, or fuel-related emissions for low- to medium-temperature applications. Some commercially available transition technologies also reduce emissions for space heating or mechanically used energy, but these are not considered here.

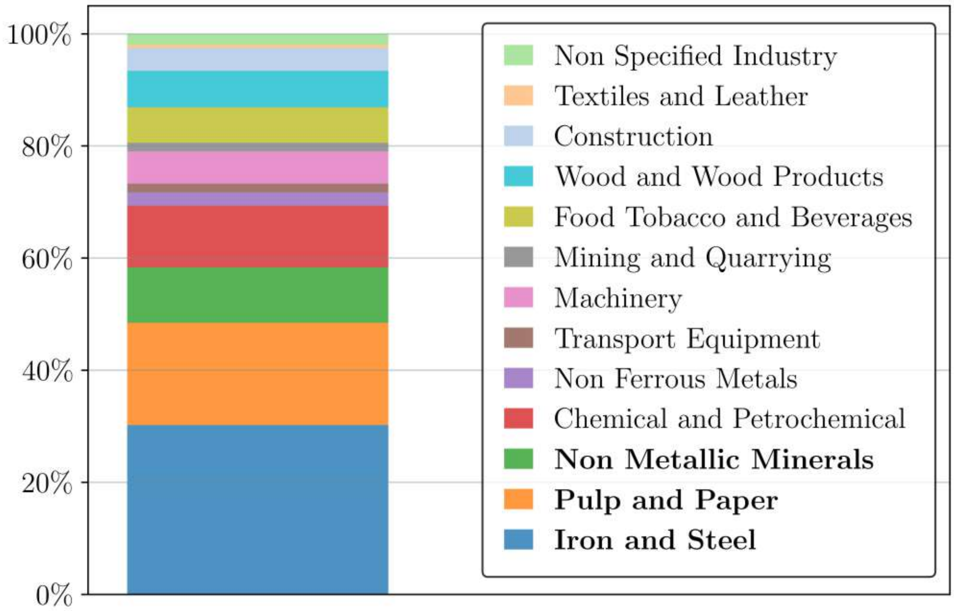

Figure 3.2: Share of the total energy demand of the industrial sectors in Austria in 2022, (StatistikAustria, 2022)

As already stated in section 2.1, Austria's industry has a total annual energy demand of 112 TWh and GHG emissions of 32 $MtCO_2$. Figure 3.2 shows the share of the energy demand of the different sectors of the industry. A crucial part of this work is the literature review on the composition of the energy demand in every sector and the options for decarbonization. As every sector has a heterogeneous product palette and a variety of processes, it is important to limit the scope of this thesis to three.
In the diagram marked are the industrial sectors chosen to be analyzed in this work. First, the Iron and Steel (IS) sector has the highest energy demand in the industry, followed by the Paper and Pulp (PP) sector and the Non-Metallic Minerals (NMM),

whereas in the last sector, solely the Cement industry is evaluated. These three energy-intensive sectors combined account for about 58 % of the industry's energy demand in Austria and for 64 % of total GHG emissions, which is, besides other, the main reason for this choice (StatistikAustria, 2022). IS sector alone consumes about 10 % of Austria's final energy.

Another reason for this selection is the decarbonization potential that these sectors show. For example, in the IS sector, as the emissions from steel production stem mainly from coal-powered blast furnaces, the emission reduction potential with other furnaces is very high.
The produced goods are assumed to be homogeneous in every one of these three sectors, and the specific energy demand per tonne output is averaged, which is a simplification. For this purpose, the non-metallic minerals sector is reduced to the most significant cement production sites, which account for 83 % of overall energy consumption and 94 % of global CO_2 emissions in this sector (Mobarakeh and Kienberger, 2022).
Of course, some sectors play a vital role in the energy system but are not examined here. For example, the chemical and petrochemical sector has great potential for decarbonization and functioning as a CO_2 sink for other sectors. Another example of decarbonization in the past is the aluminum industry, which reduced its CO_2 emissions from 150 kt in 1990 to 4.86 kt in 2020 due to a termination of primary aluminum production in Austria since 1992. (Umweltbundesamt, 2023a)

To summarize the chosen industrial sectors, an overview of the most important data is given in table 3.1, where the annual production rate, the energy demand, and the CO_2 emissions of the respective industrial sector in Austria are presented.

Industry sector	**Main product**	**Production** [Mt]	**Energy demand** [TWh]	**CO_2 emissions** [Mt]
Iron and Steel	Crude Steel	7.4	35.1	11.8
Pulp and Paper	Paper Products	5	22.5	1.9
Cement	Portland Cement	5.23	4.4	2.7

Table 3.1: Overview of the annual production, energy demand, and emissions in the analyzed key sectors in Austria in 2019.

3.2.1 Iron & Steel

Introduction of the sector

The Austrian IS industry had a production of 7.4 Mt of crude steel in 2019 with a total energy demand of 35.1 TWh (88 % comes from fossil fuels) and CO_2 emissions of 11.8 Mt. The contribution of steel production to Austria's total GHG emissions was 14 %, and it therefore played a vital role in the development of Austria's emissions in the past years. In fact, in 2021 the CO_2 emissions from IS were 61 % above the level of 1990 (**anderl˙austrias˙2023**). On the other hand, the higher efficiency of the processes can be seen, as the annual production has risen by 84 % at the same time.

There are two main routes for steel production. The primary route is steel production from iron ore via blast furnace/basic oxygen furnace (BF/BOF), and the secondary route is using recycled scrap steel in an electric arc furnace (EAF). 90 % of the produced steel in Austria is manufactured through the primary route, and there are five BF/BOF combinations at two locations from one company in Austria, three of them at voestalpine in Linz and two at voestalpine Donawitz in Leoben. As table 3.2 suggests, there are three more steel-producing sites, all of which are using an EAF.

Industrial site	**Location**
voestalpine Stahl Linz	Linz
voestalpine Sathlwerk Donawitz	Leoben
Marienhütte	Graz
Böhler Edelstahl	Kapfenberg
Breitendorf Edelstahl	Mitterdorf im Mürztal

Table 3.2: List of industrial sites in the IS sector in Austria. (*Roadmap Industrie* 2014)

The BF/BOF route involves the following process steps: Raw material preparation, iron making, and steel production. In the first stage, coal is converted into coke in a coke oven, producing not only coke but also byproducts like coke oven gas, which can be reused for heating processes as its operating temperature is between 1150 °C and 1350 °C (highest heating value of any process gas). The iron ore, later used in the reduction process, is also prepared in a sinter or pellet plant, where the product is crushed and homogenized. The coke and the iron ore are then fed into the BF to reduce the iron oxide from the iron ore to produce metal iron. Here coke is used as a reducing agent to remove the oxide from the iron ore[1]. In the BOF, the iron is again injected with purified oxygen to reduce the carbon content in the iron and produce crude steel. In

[1] Chemical reaction equation for reducing iron ore (Fe_2O_3) with carbon monoxide (CO) to produce iron (Fe) and CO_2 : $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$. (Bhaskar, Assadi, and Nikpey Somehsaraei, 2020)

the end, the steel is refined and cast into the semi-finished products to be hot-rolled into the finished products. (Chan, Kantamaneni, and Allington, 2015)
The EAF route utilizes recycled ferrous materials like scrap steel or recycled iron as basic materials. These materials are melted in the EAF using electricity with a high electric current to produce crude steel. This is again refined, cast, and hot-rolled.

Most of the CO_2 emitted in IS are process-related (87.6 %) and come from the primary route when using coal as a reducing agent; the rest of the emissions are fuel-combustion-related and come from using fossil fuels to generate process heat. The GHG emission intensity of the primary route in Austria is 1.7 $\frac{tCO_2}{tSteel}$ and for the EAF route, it is 0.1 $\frac{tCO_2}{tSteel}$. As for the consumed energy carriers, the BF/BOF route consumes 4.7 $\frac{MWh}{tSteel}$, with most of it coming from fossil fuels, mainly coal. The energy demand in the EAF route is 0.97 $\frac{MWh}{tSteel}$, with the leading energy carrier being electricity.

Sustainable energy carrier alternatives and decarbonization options

Most emissions in the IS sector are process-related because coal is used as a reducing agent, and most of the remaining emissions occur in industrial high-temperature furnaces. Table 3.3 presents the sector's transition technologies considered in this work, which pillar they are associated with, and the current TRL. Also, and this is one of the most critical factors for this optimization, the emission reduction potential is displayed, which is the percentage of how much the emissions are reduced after installing this technology. The last factor is the change in the specific energy demand (ΔSEC), which is positive when the energy demand is reduced and negative when it increases with the implementation of the transition technology.

Process-related: According to the literature, the most promising technologies for deep decarbonization of the IS sector are switching to less carbon-intensive fuels and carbon capture and storage or utilization.
An already well-researched technology is Direct Reduction Iron (DRI) with NG[2]. Compared to the BF/BOF route, DRI with NG can reduce emissions by up to 40 %. NG is used as a reducing agent instead of coal, and the iron is melted in an EAF instead of the BOF, so the demand for coal is reduced, and the demand for NG and electricity

[2]Direct reduction iron with NG (CH_4) consists of two stages. The first stage is the steam methane reforming, where NG is reformed with water to carbon monoxide and hydrogen: $CH_4 + H_2O \rightarrow CO + 3H_2$. The second stage combines reduction with carbon monoxide and reduction with hydrogen. In opposition to the chemical reaction of reducing iron ore with carbon monoxide producing iron and CO_2 , the direct reduction of iron with hydrogen (H_2) results in iron and water (H_2O): $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$. (Bhaskar, Assadi, and Nikpey Somehsaraei, 2020)

Technology	Pillar	TRL	Emission reduction potential	ΔSEC
Energy Efficiency Improvement	EEI	9	15 %	26 %
Electrification	ELEC	4	98 %	31 %
Smelting Reduction Process	FS	7	20 %	
Top Gas Recycling	FS	7	22 %	
Direct Reduction with Natural Gas	FS	9	40 %	
Direct Reduction with Hydrogen	FS	6	95 %	20 %
Carbon Capture	CCS	7	50 %	

Table 3.3: List of transition technologies of the IS sector

increases. Nevertheless, the decarbonization potential is limited, as the reducing with NG produces CO_2 as a byproduct. Even more sufficient decarbonization is achieved through DRI with hydrogen, where hydrogen is used as a reducing agent for the iron ore, and the main byproduct is water. The emission reduction potential is up to 95 %, depending on the hydrogen. Although it is not yet commercially available, this technology is highly anticipated for future use and is predicted to be available after 2030. Electrification of the reduction process is also in the works; an electro-chemical process is used here to reduce the iron ore. This technology can potentially reduce emissions up to 98 % and be the most energy-efficient way of ironmaking.
The CO_2 generated in different parts of the steelmaking process can also be captured in various ways to reduce up to half of the emissions. It is not possible to combine CCS with every technology because the CO_2 is emitted from multiple sources. Still, one way to capture it is by combining it with technologies like DRI-NG or Top Gas Recycling. Another way would be to utilize the CO_2 contained in the different furnace exhaust gases (coke oven gas, blast furnace gas, basic oxygen furnace gas). Top Gas Recycling is a way of reusing the exhaust gas from the top of the BF inside the BF as part of the reducing agent (Junjie, 2018). The Smelting Reduction Process replaces air in the reduction process with purified oxygen, which reduces iron ore and coal powder and increases the concentration of CO_2 in the BF exhaust gas to combine it with CCS.

Fuel-related for high-temperature process heat: Installing technologies to increase the energy efficiency of the process is one key factor for short-term decarbonization. This includes measurements like waste heat or excess steam recovery and process integration measurements and can help to reduce emissions by up to 15 % and the energy demand up to 26 %.

3.2.2 Pulp & Paper

Introduction of the sector

In Austria, 5 Mt of paper and paper products are produced every year, consuming 22.5 TWh of energy (third-largest industrial energy demand) and emitting 2.7 Mt of CO_2 . Of the energy demand, about 30 % is fossil fuels, 42 % biofuels like biogas, biomass, or black liquor, and the rest is electricity. More than half of the power consumed in the PP mill is generated through the internal combined heat and power (CHP) plant, where black liquor and gas are utilized to produce electricity and process steam. The Austrian PP sector is self-sufficient in process steam generation. Excess heat and produced surplus electricity can be fed into a district heating or electricity grid. Almost all of the emissions in the PP sector are fuel-related, with only 3 % being process-related from the used limestone.

Industrial site	Location	Industrial site	Location
Sappi Gratkorn	Gratkorn	Mondi Neusiedler	Amstetten
AustroCell	Hallein	Ybbstaler Zellstoff	Kematen a.d. Ybbs
Brigl & Bergmeister	Niklasdorf	Smurfit Kappa	Ansfelden
Essity Austria	Pernitz	Norske Skog Bruck	Bruck an der Mur
Dr. Franz Feuerstein	Traun	Zellstoff Pöls	Pöls-Oberkurzheim
W. Hamburger	Pitten	Poneder	Amstetten
Laakirchen Papier	Laakirchen	Profümed	Grimmenstein
Lenzing Papier	Lenzing	Rondo Ganahl	Frastanz
Mayr-Melnhof Karton	Frohnleiten	Salzer Papier	St. Pölten
Merckens	Schwertberg	UPM-Kymmene	Laakirchen
Mondi Frantschach	Frantschach	Papierfabrik Wattens	Wattens

Table 3.4: List of industrial sites in the PP sector in Austria. (Austropapier, 2024)

Paper production plants have a variety of end-products like pulp, newsprint paper, hygiene paper, packaging material, labels, stationery, or cardboard, with many different production processes. In Austria, there are 22 production sites of those different paper products, as seen in table 3.4. In this work, the output product is assumed to be the same paper in every site with the same specific energy demand and specific emissions. The three main steps in the papermaking process are raw material preparation, pulp production, and papermaking. The primary raw material used in paper making is pulp, which is made from wood by reducing wood logs to small chips or by repulping recycled paper. The pulping phase can be carried out by mechanical, chemical, or semi-chemical pulping. The quality and further use of the pulp highly depend on the form of pulping. In mechanical pulping, the wood logs or chips are ground with water, which is the cheapest form of pulping but produces the weakest fibers, resulting in lower-grade paper, like newsprint. In chemical pulping, the wood chips are heated with chemicals under high pressure, generating higher-graded fibers but a lower pulp yield from the wood source (Chan, Kantamaneni, and Allington, 2015). The benefit of the lower yield is that the so-called black liquor, which is a byproduct, can be used for heat recovery. Semi-chemical pulping is a combination of mechanical and chemical pulping. The pulp is then either delivered directly to the paper mill in an integrated mill (which is more energy efficient) or dried and shipped to a market pulp. In the papermaking step, the pulp is dried, pressed, and coated in the paper mill.

The drying process takes up about 67 % of the total energy demand in the PP sector (75 % in the papermaking step itself), and chemical pulping makes up for 10 %, and mechanical pulping for 4 %. The emission factor of the whole process lies at 0.38 $\frac{tCO_2}{tPaper}$ and is therefore relatively low because emissions from biofuel consumption are not considered. The specific energy demand is 4.5 $\frac{MWh}{tPaper}$.

Sustainable energy carrier alternatives and decarbonization options

A large part of the energy demand is consumed in the drying section of the papermaking for low/medium-temperature steam. Also, almost all emissions in this sector are fuel-related, so most transition technologies considered here are for low/medium-temperature heat applications. Table 3.5 shows an overview of the transition technologies in the PP sector and their most important data.

Process-related: CCS/CCUS is an option that can be adopted in different parts of the paper mill. The emissions from the recovery boiler or the pulp mill can be captured or utilized. Combined with a high deployment of biogas use, up to 98 % of CO_2 emissions can be abated.

Fuel-related for low/medium-temperature process heat: Black Liquor Gasification is an alternative to commonly used recovery boilers. Here, the black liquor from the pulping is gasified and pressurized and used as an energy source for steam generation (Naqvi, Yan, and Dahlquist, 2010). The potential for emission reduction is at 22 % and demand reduction at 17 %. Other new drying techniques in papermaking, which all have an emission reduction potential of 20 % and demand reduction potential of 10 %, are Superheated Steam Drying, Gas-Fibred Dryers or Microwave Drying. Superheated

Technology	Pillar	TRL	Emission reduction potential	ΔSEC
Black Liquor Gasification	EEI	8	22 %	17 %
Electric Boiler	ELEC	9	20 %	
Heat Pump	ELEC	7	75 %	50 %
Carbon Capture	CCS	6	98 %	
Superheated Steam Drying	EEI	3	20 %	10 %
Gas-Fired Fibres	EEI	6	20 %	10 %
Microwave Drying	EEI	3	20 %	10 %

Table 3.5: List of transition technologies of the PP sector

Steam Drying replaces the needed air for the drying process with heated steam, which improves heat recovery and enhances efficiency. Gas-Fired Fibres use hot gas instead of steam to heat the dryers. Microwave Drying uses microwave radiation for the drying process.
The electrification of low- or medium-temperature heating processes is already available and has a high efficiency, so Electric Boilers have the potential to be adapted in the near future to replace fossil fuels. Heat Pumps for industrial applications are still being explored because, up to now, it is possible to produce heat of 100 °C with a good coefficient of performance. In the future, using heat pumps for the drying process could reduce emissions by 75 % and cut energy demand in half.

3.2.3 Cement

Introduction of the sector

The annual production rate of Austria's cement plants is 5.2 Mt of portland cement[3], distributed over 11 construction sites, shown in table 3.6. With 2.7 Mt CO_2 emissions per year, 7 % of global GHG emissions come from cement production. Two-thirds of the GHG emissions in the cement sector are process-related and come from clinker production. Because of that, the cement sector is a so-called hard-to-abate sector, and the process-related emissions can, so far, only be reduced by lowering the clinker-to-cement ratio. Although the Austrian cement sector has one of the lowest emission factors in the

[3]Portland cement is the most common form of cement since the 19th century and is made from portland clinker. (Shi, Jiménez, and Palomo, 2011)

world, it is the country's second-largest CO_2 emitter. 86 % of the final energy is thermal energy - with 18 % coming from fossil fuels, the rest from alternative fuels like plastic waste or old tires - and the rest is electricity.

Industrial site	Location
Alpacem Zement Wietersdorf	Klein St. Paul
Alpacem Zement Peggau	Peggau
Baumit	Waldegg
Danucem	Wien
Holcim Mannersdorf	Mannersdorf am Leithagebirge
Holcim Retznei	Ehrenhausen an der Weinstraße
Kirchdorfer Zementwerk	Kirchdorf an der Krems
Leube	Grödig
Schretter und Cie	Vils
SPZ Eiberg	Kirchbichl
Zementwerk Hatschek	Gmunden

Table 3.6: List of industrial sites in the cement sector in Austria. (VÖZ, 2024)

The three stages of cement production are raw material preparation, clinker, and cement production. The primary raw materials like clay, limestone, and chalk must be pulverized in a grinder before further use. During the clinker production, limestone is heated to produce lime in a clinker kiln[4]. The three types of clinker kilns are wet, semi-wet, and dry, with the wet kiln being the most energy-intensive. In Austria, all clinker kilns are dry. The dry kiln needs a preheater, which heats the raw material to 900 °C, reusing the excess heat for energy efficiency. Then, in the precalciner, the clinker is produced at temperatures above 1400 °C. The clinker is then cooled fast to 100-200 °C, leaving the opportunity to use the excess heat again. The cement production step mixes the clinker with gypsum or fly ash.

Austria's relatively low specific emissions of 0.51 $\frac{tCO_2}{tPaper}$ are rooted in the low clinker-to-cement ratio of 69 %, achieved using more alternative materials like fly ash in the final step. The overall specific energy demand, which is mainly used for heat generation in the kilns, is 0.84 $\frac{MWh}{tCement}$.

Sustainable energy carrier alternatives and decarbonization options

The cement sector is hard to abate because a significant part of the emissions comes from the process, more precisely from the chemical reaction in clinker production. So,

[4]Chemical reaction equation for inducing heat to limestone ($CaCO_3$) to get lime (CaO) and CO_2 : $CaCO_3 + \text{energy} \rightarrow CaO + CO_2$

two main pathways for decarbonization in this sector are CCS and reducing the clinker ratio in the finished cement. Table 3.7 shows the considered transition technologies in this sector. Most technologies here deal with clinker production or with carbon capture. The other can be applied in high-temperature heat generation because the cement sector mainly uses high-temperature processes.

Technology	Pillar	TRL	Emission reduction potential	ΔSEC
CCS - Oxyfuel	CCS	6	90 %	−15 %
CCS - Amine Gas Treating	CCS	7	95 %	−40 %
Electrification	ELEC	4	40 %	
Waste Heat Recovery	EEI	8	5 %	5 %
Advanced Grinding	EEI	6	5 %	5 %
NB - Carbonate Calcium Silicates	EEI	7	20 %	
NB - Magnesium Silicates	EEI	3	20 %	
NB - Alkali Activated Binders	EEI	9	20 %	

Table 3.7: List of transition technologies of the cement sector

Process-related: Best available technologies can improve the process and reduce the emissions and the energy demand by 10 %. Waste Heat Recovery captures the heat from the kiln and the clinker cooler and reuses it or generates electricity, producing steam. Advanced Grinding makes the grinding process in the material preparation more efficient and reduces the emissions from mechanical energy demand.
CCS technologies for process-related emissions can be applied post-combustion or as oxyfuel combustion. In Oxyfuel technology, pure oxygen is used to burn fuel instead of air. This increases the concentration of CO_2 in the exhaust gas, making carbon capture easier. 90 % of the emissions can be captured, but the energy demand increases by 15 % because the technology to capture the emissions needs a lot of energy. The Amine Gas Treating is post-combustion and based on a cyclic absorption process. The CO_2 is absorbed, mixed with amine, and liquified (DEAE, 2021). This method can capture up to 95 % of the emissions but needs a lot of energy, increasing the demand of the plant by 40 %.
To increase the quality of the clinker, new binder materials can be used, which can reduce the emissions up to 100 %. Carbonate Calcium Silicates use less lime in the clinker, which makes it possible to use lower burning temperatures in cement produc-

tion. Magnesium Silicates, which are only in the research phase, could be used instead of limestone in the clinker to reduce emissions drastically. Alkali Activated Binders are binders that can produce the Portland cement much more energy efficiently.

Fuel-related for high-temperature process heat: With a low TRL and therefore not applicable in the near future, electrification of the heat generation in the kiln by adapting plasma technologies (like in an EAF) could decarbonize the fuel-related emissions when using carbon-free electricity.

3.3 Techno-economic optimization model for industry's transformation pathways

This section gives and explains the mathematical formulation of the cost-minimizing optimization model. The model is formulated as a Mixed Integer Linear Program because implementing transformation technologies is a binary decision for some pillars. Explicitly, when a heating generation process is electrified or switched to another fuel, it ensures a complete technology change. Investments into and implementation of other pillars like EEI can be made linearly.

3.3.1 Mathematical formulation and objective

Objective function

The objective function, given in equation 3.1, minimizes the sum of the investment costs, the costs of GHG emissions, the energy carrier costs, and penalty payments for uncovered demand. The values are summed over the years y, the industrial sites s, the energy carriers c, and the mix of the energy carriers m. The last term of the equation is used to prevent the solution of the model from being infeasible if the availability of an energy carrier is restricted for a location but needed for the process. In that case, the energy carrier would be transported through other channels, but the model can only differentiate between what is available through pipelines and what is not. The price for penalty payments $c^{penalty}$ is very high, so the conscious withholding of demand or investments into technologies is never profitable.

$$\min_{\mathcal{X}} \sum_{y} \left(\sum_{s} \left(\gamma^{inv}_{y,s} + c^{CO2}_{y} \cdot \rho^{CO2}_{y,s} \right) + \sum_{c} \left(\sum_{m} \left(c^{fuel}_{y,c,m} \cdot \rho^{mix}_{y,c,m} \right) + \rho^{uncovered}_{y,s,c} \cdot c^{penalty} \right) \right) \tag{3.1}$$

$$\mathcal{X} = \left[\rho^{dem}_{y,s,c}, \rho^{mix}_{y,c,m}, \rho^{CO2}_{y,s}, \eta^{dem}_{y,s,c}, \eta^{CO2}_{y,s}, \gamma^{inv}_{y,s}, \sigma^{tech}_{y,s,t}, \sigma^{tech,bin}_{y,s,t}, \sigma^{inv}_{y,s,t}, \rho^{uncovered}_{y,s,c}\right] \tag{3.2}$$

In equation 3.2, the decision variables of the optimization model are presented, with a full list of them in table 3.9. In this mathematical formulation, decision variables are always referred to with Greek letters, and parameters are written in Latin letters. $\rho^{dem}_{y,s,c}$ is the annual energy carrier demand of a site, $\rho^{mix}_{y,c,m}$ is the annual energy carrier demand of the system, depending on the energy mix m, which represents either imported or domestically produced carriers. $\rho^{CO2}_{y,s}$ are the carbon emissions per site, $\eta^{dem}_{y,s,c}$ and $\eta^{CO2}_{y,s}$ are the specific energy demand and the specific emissions of a site, $\gamma^{inv}_{y,s}$ are the annual investment costs into transformation technologies and $\rho^{uncovered}_{y,s,c}$ is the uncovered energy demand. All these variables are positive continuous variables. $\sigma^{tech}_{y,s,t}$ is a continuous variable between 0 and 1, representing the percentage of installment of a transition technology in a site at a given year. $\sigma^{tech,bin}_{y,s,t}$ also displays an installed technology in a site but is binary to ensure binary installation decisions for pillars ELEC and FS, as described above. $\sigma^{inv}_{y,s,t}$ is again a continuous variable between 0 and 1; it is an auxiliary variable set only for a newly installed technology to calculate the annual investment costs.

Constraints

Specific demand and specific GHG-emissions:

Equations 3.3 and 3.4 are the model's central and most important constraints. The first one calculates the specific energy carrier demand of a site $\eta^{dem}_{y,s,c}$ every year. The product of the specific default energy demand of a site $h^{dem,site}_{s}$ and the percentage of used energy carriers $h^{carrier,site}_{s,c}$ determine the specific energy demand per energy carrier. The term in the first bracket is responsible for changing the energy demand with an installed technology; the term in the second bracket changes the usage of energy carriers when installing a technology. The change of energy carrier use with a technology $h^{carrier,tech}_{t,c}$ is zero for pillars EEI and CCS, so the variable $\sigma^{tech}_{y,s,t}$ is not used in the second part of the equation in that case. If the pillar of the technology is ELEC or FS, $\sigma^{tech}_{y,s,t}$ is binary (equation 3.10) and can therefore be multiplied by itself, thus preventing the equation from being non-linear.

$$\begin{aligned}\eta^{dem}_{y,s,c} = h^{dem,site}_{s} \cdot &\left(1 - \sum_{t \in \mathcal{T}_{s,TRL}} h^{dem,tech}_{t} \cdot \sigma^{tech}_{y,s,t}\right) \\ &\cdot \left(h^{carrier,site}_{s,c} - \sum_{t \in \mathcal{T}_{s,TRL}} h^{carrier,tech}_{t,c} \cdot \sigma^{tech}_{y,s,t}\right) \quad : \forall y, s, c\end{aligned} \tag{3.3}$$

$$\eta^{CO2}_{y,s} = h^{CO2,site}_{s} \cdot \left(1 - \sum_{t \in \mathcal{T}_{s,TRL}} h^{CO2,tech}_{t} \cdot \sigma^{tech}_{y,s,t}\right) \quad : \forall y, s \tag{3.4}$$

Equation 3.4 works similarly to the first part of the upper equation. The installation of a transition technology reduces the specific emissions by some percentage, specified by $h^{CO2,tech}_{t}$.

Annual demand and GHG-emissions:
In the equations 3.5 and 3.7, the annual energy carrier demand $\rho^{dem}_{y,s,c}$ and the annual GHG-emissions $\rho^{CO2}_{y,s}$ are calculated as a product of the produced output in a site and the specific energy carrier demand and GHG-emissions. In the first equation, the uncovered demand is also considered. Formular 3.6 generates a connection between the annual energy carrier demand per site and the annual energy demand in the system per energy origin $\rho^{mix}_{y,c,m}$.

$$\rho^{dem}_{y,s,c} = q^{out}_{y,s} \cdot \eta^{dem}_{y,s,c} - \rho^{uncovered}_{y,s,c} \quad :\forall y, s, c \tag{3.5}$$

$$\sum_{s} \rho^{dem}_{y,s,c} = \sum_{m} \rho^{mix}_{y,c,m} \quad :\forall y, c \tag{3.6}$$

$$\rho^{CO2}_{y,s} = q^{out}_{y,s} \cdot \eta^{CO2}_{y,s} \quad :\forall y, s \tag{3.7}$$

Investment decisions into new technologies:
In equation 3.8, the auxiliary variable $\sigma^{inv}_{y,s,t}$ is set to $\sigma^{tech}_{y,s,t}$, only when a new technology is installed. It is 0 for already installed technologies and also 0 for technologies being removed. This variable is then used in calculation 3.9 to calculate the annual investments into transition technologies per site.

$$\sigma^{inv}_{y,s,t} \geq \sigma^{tech}_{y,s,t} - \sigma^{tech}_{y-1,s,t} \quad :\forall y > 0, s, t \tag{3.8}$$

$$\gamma^{inv}_{y,s} = q^{out}_{y,s} \cdot \sum_{t} \sigma^{inv}_{y,s,t} \cdot c^{inv}_{t} \quad :\forall y, s \tag{3.9}$$

Limitations for installing transformation technologies:
As already mentioned, the variable for installed technologies needs to be binary for pillars ELEC and FS. The subset $\mathcal{T}_{pillar}$ represents such technologies and equation 3.10 forces $\sigma^{tech}_{y,s,t}$ to be binary in that case. It is also important that only one technology is installed that changes the energy carrier of the process. For example, one furnace in a steel production site can't be replaced by DRI-NG and DRI-H_2 simultaneously. Equation 3.11 ensures this by limiting the sum of technologies of these pillars installed

in a site to 1.

$$\sigma^{tech}_{y,s,t} = \sigma^{tech,bin}_{y,s,t} \quad :\forall y, s, t \in \mathcal{T}_{pillar} \tag{3.10}$$

$$\sum_{t \in \mathcal{T}_{pillar}} \sigma^{tech}_{y,s,t} \leq 1 \quad :\forall y, s \tag{3.11}$$

Infrastructure related changes and constraints:
This category represents the constraints for the availability of energy carriers. Equation 3.12 limits the maximal available energy carrier per mix, which can set an upper limit for the domestically produced green gases and hydrogen.
Equation 3.13 focuses on the network itself and sets the demand on a location to 0 if the energy carrier is not available there.

$$\rho^{mix}_{y,c,m} \leq q^{max}_{y,c,m} \quad :\forall y, c, m \tag{3.12}$$

$$\rho^{dem}_{y,s,c} = 0 \quad :\forall y, s, c \notin \mathcal{C}_s \tag{3.13}$$

3.3.2 Sets and decision variables

Tables 3.8, 3.9, and 3.10 list the sets, subsets, variables, and parameters used in the mathematical formulation of the optimization model. The usage in the equation is already explained above.

Sets	
$y \in \mathcal{Y} = \{2020, \ldots, 2040\}$	Years, index by y
$s \in \mathcal{S} = \{1, \ldots, S\}$	Industrial sites, index by s
$t \in \mathcal{T} = \{1, \ldots, T\}$	Transformation technologies, index by t
$c \in \mathcal{C} = \{1, \ldots, C\}$	Energy carriers, index by c
$m \in \mathcal{M} = \{1, \ldots, M\}$	Mix of the energy carrier origin, index by m
Subsets	
$\mathcal{T}_{s,TRL} \subseteq \mathcal{T}(s, TRL)$	Subset of technologies which are in the same branch as the regarding site and have a $TRL \geq 8$, index by t
$\mathcal{T}_{pillar} \subseteq \mathcal{T}(pillar)$	Subset of technologies which have the pillar 2 or 3, index by t
$\mathcal{C}_s \subseteq \mathcal{C}(s)$	Subset of energy carrier that is available at a site s, index by c

Table 3.8: Sets and subsets of the model

Variable	Description	Unit
$\rho^{dem}_{y,s,c}$	Annual energy demand per site s and energy carrier c	MWh
$\rho^{mix}_{y,c,m}$	Annual energy demand per energy carrier c and energy mix m	MWh
$\rho^{CO2}_{y,s}$	Annual GHG-emissions per site s	t
$\eta^{dem}_{y,s,c}$	Specific energy demand per year y, site s and energy carrier c	MWh/t_{output}
$\eta^{CO2}_{y,s}$	Specific GHG-emissions per year y and site s	t/t_{output}
$\gamma^{inv}_{y,s}$	Annual investments into transformation technologies per site s	€
$\sigma^{tech}_{y,s,t}$	Variable determining the grade of a technology t being installed in a site s in a year y	1
$\sigma^{tech,bin}_{y,s,t}$	Binary variable determining the grade of a technology t being installed in a site s in a year y	1
$\sigma^{inv}_{y,s,t}$	Auxiliary variable determining if a new technology t is being installed in a site s in a year y	1
$\rho^{uncovered}_{y,s,c}$	Auxiliary variable determining the amount of energy demand not covered in a site s	MWh

Table 3.9: Decision variables of the model

Parameters	Description	Unit
$q^{out}_{y,s}$	Annual production rate of a site s	t_{output}
$q^{max}_{y,c,m}$	Maximal annual energy available for a carrier c and a mix m	MWh
$h^{dem,site}_{s}$	Specific default energy demand of a site s	MWh/t_{output}
$h^{dem,tech}_{t}$	Change of the specific energy demand with a technology t	1
$h^{carrier,site}_{s,c}$	Ratio of energy carriers c used in a site s	1
$h^{carrier,tech}_{t,c}$	Change of the ratio of energy carriers c with a technology t	1
$h^{CO2,site}_{s}$	Specific default GHG-emissions in a site s	t/t_{output}
$h^{CO2,tech}_{s}$	Change of the specific GHG-emissions with a technology t	t/t_{output}
c^{inv}_{t}	Investment costs into a new technology t	€/t_{output}
c^{CO2}_{y}	Annual CO_2 costs	€/t
$c^{fuel}_{y,c,m}$	Annual costs for the energy carrier c per mix m	€/MWh
$c^{penalty}$	High costs for energy demand not covered by $\rho^{dem}_{y,s,c}$	€/MWh

Table 3.10: Parameters of the model

4 Scenarios: "Electrification" and "Domestic Green Gases"

The goal of the transformation pathways in the analyzed scenarios *Electrification* and *Domestic Green Gases* is to find the optimal technology transformation pathways in the Austrian industrial key sectors under the influence of the availability of the energy network infrastructure, the energy carrier in the grid, and the energy carrier costs. In the mathematical formulation, the equations 3.12 and 3.13 represent the constraints regarding the availability, and the objective function considers the energy carrier costs. The connection to the gas grid is included in this calculation via the subset $\mathcal{C}_s$, which is set true for industrial sites located in a Local Administrative Unit (LAU) with a connection to the grid. There is no secured information on whether the industrial site itself has a connection to the grid or not, but that can be assumed because these are all large consumers with NG demand. Some transition technologies, as well as already installed technologies, rely on different energy carriers, such as NG or hydrogen. Therefore, the current or future availability of the energy carriers and the grid infrastructure is crucial in deciding whether a transition technology can be supplied by the energy carrier or if a transition technology is necessary in the future to deal with declining accessibility to an energy carrier. The amount and price of an energy carrier have a similar effect on the transformation pathways. In this work, the maximal amount of the energy carrier is not hard-constrained, but the index of the energy mix m differentiates between domestically produced and imported, so when the limit of the domestically produced energy carrier is reached, the rest needs to be imported, as the maximal available imported energy carrier is not constrained. The price, though, varies between those two types of energy carriers.

The basic concept of the storylines of the scenarios stems from the research published in the Gas-Infra study (Zwickl-Bernhard et al., 2024) and two of the four scenarios used there, *Electrification* and *Decentralized Green Gases*. A brief summary of this work is available in the section 2.1.3. The data for the infrastructure in the scenarios described below is sourced from the article and the full report published in (BMK, 2023). Basically, what differs between the scenarios here and, therefore, is relevant from the Gas-Infra study is the reduction of the gas grid compared to the grid in 2020 on the one hand and the expansion of the hydrogen grid on the other. Also, the amount of domestically

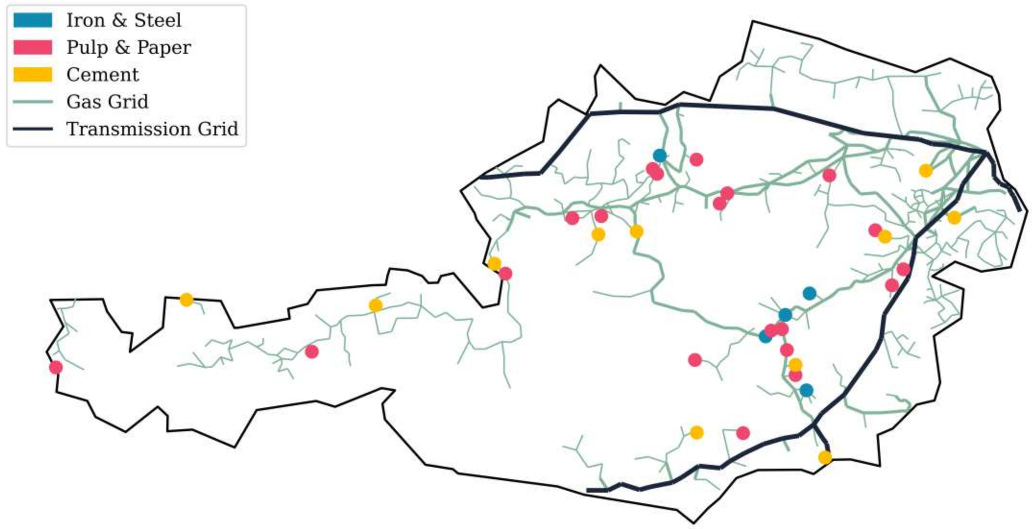

Figure 4.1: Network of the Austrian gas grid with the industrial sites of the IS, PP, and cement sector in 2020

produced renewable gases and hydrogen differs, and the network charges are calculated based on the respective scenario, which is the basis for some assumptions in this thesis. One other aspect that would be included in the definition of energy network infrastructure but is not considered in this work is the electricity grid. The reason for this is that the electricity grid itself is expected to be sufficient for every requirement of the connection of industrial sites. Recent projects, like the connection of steel production site voestalpine Linz to the 220 kV transmission grid (APG, 2024), confirm that the Transmission System Operator (TSO) is trying to make electrification in the industry possible. The increasing electricity demand and the challenges sourcing from this are out of the scope of this thesis, and thus not considered.
In 2020, the gas grid in Austria had a total length of 1449 km at the high-pressure level and 3218 km at the mid-pressure level. Figure 4.1 shows the locations of the analyzed industrial sites in the key sectors and the extent of the gas grid in 2020. The black line represents the transmission gas grid, consisting of the "Trans Austria Gas Pipeline" (TAG) and the "West Austria Gas Pipeline" (WAG); the thicker green lines show the high-pressure gas grid, and the thinner lines show the mid-pressure gas grid. All industrial sites on this map are located in LAUs connected to the gas grid. The domestic production of renewable gases in 2020 is assumed to be zero; the

production of hydrogen is also zero, and there is no hydrogen grid installed at the moment in Austria. Even though the hydrogen grid is expanding at a high rate in both scenarios, the following figures only show the gas grid because a switch to hydrogen is only considered in the analyzed transition technologies for the primary route in the IS sector. There are only two steel-producing sites in Austria on the primary steel route, voestalpine Linz and Donawitz, and both these sites have a connection to the hydrogen grid in both scenarios after 2030.

	2020	2040 *Electrification*	2040 *Domestic Green Gases*
Grid length:			
Gas	4667 km	2866 km	3381 km
Hydrogen	0 km	1993 km	4864 km
Domestic production:			
Renewable Gas	0 TWh	7.4 TWh	20 TWh
Hydrogen	0 TWh	7.2 TWh	14.3 TWh
Main assumptions		Low electricity prices	Low renewable gas and hydrogen prices

Table 4.1: Grid length, domestic annual production, and main assumptions in 2020 and the scenarios *Electrification* and *Domestic Green Gases*

Table 4.1 summarizes the most critical data from the two scenarios and their main differences. The data is shown for 2020 and 2040 for both scenarios, even though network infrastructure availability, energy carrier availability, and energy carrier price are also given for 2025, 2030, and 2035 and assumed to stay constant during these five-year periods. The most important parameters include the grid length, where the stated length is the sum of the high- and mid-pressure grid, the transmission grid is not included here, the domestic annual production rate in the given year, and the assumptions regarding the energy carrier prices. The domestic annual production rate is used for $q_{y,c,m}^{max}$ to limit the maximal domestic available energy carrier in year y.
In both scenarios and all four scenarios of the Gas-Infra study, the NG demand in Austria in 2040 is supplied only by domestically produced and imported renewable gases. The ratio of renewable gases in the NG demand in this work is no endogenous decision of the calculation, but it is an exogenous parameter varying for the displayed years and amounts to 0 % (2020), 15 % (2025), 40 % (2030), 70 % (2035), and 100 % (2040). These values source from different transformation scenarios described in section 2.1.

Electrification

The *Electrification* scenario faces the most considerable reduction of the gas grid, with the idea of maximizing electricity utilization in the energy system. Figure 4.2 shows the gas grid and the respective industrial sites in this scenario, with the thick green lines reflecting the high-pressure grid and thin lines picturing the mid-pressure grid. Although the transmission line still physically exists in this scenario, it is only used for gas transport through Austria, and no access points to the lower-level grid are available. The total gas grid length in 2040 is assumed to be 964 km at high-pressure level, which is a reduction of 33.5 % compared to 2020's grid, and 1902 km at mid-pressure level, which corresponds to a reduction of 40.9 %. The total reduction of the gas grid is 1801 km, or 38.6 %. Also, as seen on the map, some industrial sites in the PP and cement sectors will not be connected to the grid in 2040, which might influence the results.

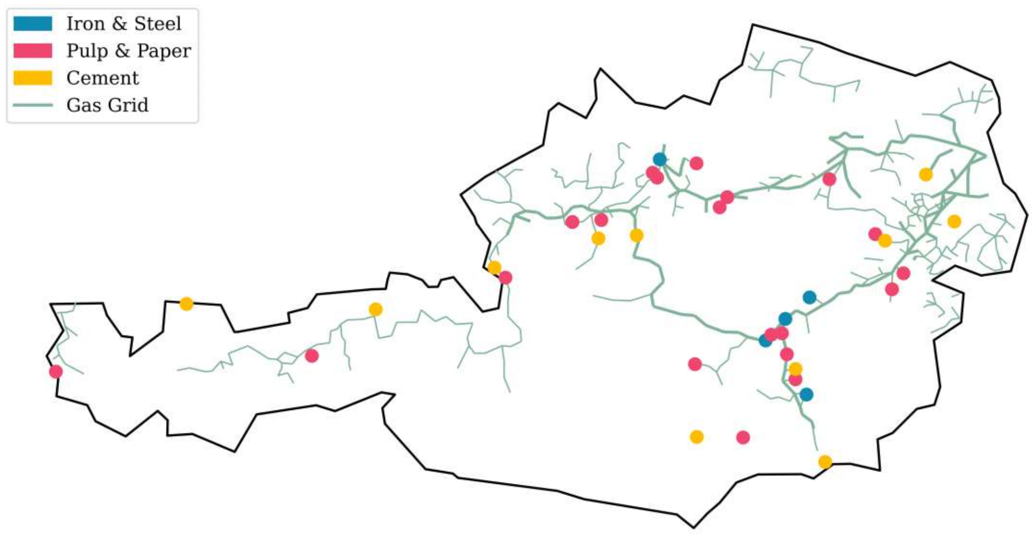

Figure 4.2: Network of the Austrian gas grid with the industrial sites of the IS, PP, and cement sector in 2040 in the scenario *Electrification*

Domestic annual production of renewable gases increases from almost zero in 2020 to 4 TWh in 2030 and 7.4 TWh in 2040, and the demand for NG or renewable gases is assumed to shrink significantly. In fact, the demand in this scenario is the lowest of all four scenarios in the Gas-Infra study and expected to be 2.6 TWh in the three key sectors in total. Although this value does not influence the results of this work, the network charges, which are the basis for the assumed energy carrier costs, are the highest in this scenario. This is why energy carrier costs for NG are higher, and because of the expected well-expended electricity grid, electricity prices are assumed to be lower. The exact prices for the energy carriers in the respective five-year periods are given in table 4.2, these prices are derived from the prices used in (Schützenhofer et al., 2024), but changed according to the respective scenario. The prices for emitting CO_2 are the same in both scenarios and increase linearly from 50 $\frac{€}{tCO_2}$ in 2021 to 400 $\frac{€}{tCO_2}$ in 2040.

	2021 [€/MWh]	2025 [€/MWh]	2030 [€/MWh]	2035 [€/MWh]
Coal	20	20	20	20
NG / GG	40	40	40	40
Other fuels	17.5	17.5	17.5	17.5
Electricity	60	60	60	60
Hydrogen	200	140	110	100

Table 4.2: Energy carrier costs for the given five-year periods in the *Electrification* scenario

The hydrogen grid is increasing from zero to 1993 km in 2040 and will be well established then. The production of hydrogen in Austria also increases significantly from zero in 2020 to 3.8 TWh in 2030 and 7.2 TWh in 2040. In this scenario, hydrogen is an important energy carrier because a high penetration of electricity promotes electrolyzers. However, the expected hydrogen demand is still lower than in the *Domestic Green Gases* scenario, so the hydrogen costs are higher here.

Domestic Green Gases

The gas grid in the *Domestic Green Gases* scenario is also shrinking compared to 2020, but the decrease is less significant than in the *Electrification* scenario. Figure 4.3 shows Austria's industrial locations and the gas grid with high-pressure and mid-pressure pipelines in 2040. According to this illustration, only one cement production site (Alpacem Zement Wietersdorf) is not connected to the gas grid here. The gas grid is reduced to 974 km at high-pressure level (32.8 % decrease) and by 25.2 % to 2407 km at mid-pressure level, which accounts for a total reduction of the gas grid of 1286 km or 27.6 %.

Domestic gas production increases here from zero in 2020 to 5 TWh in 2030 and 20.3 TWh in 2040, which is almost three times as much as in the *Electrification* scenario. In the Gas-Infra study, the network charges for gas in 2040 are only half of them of

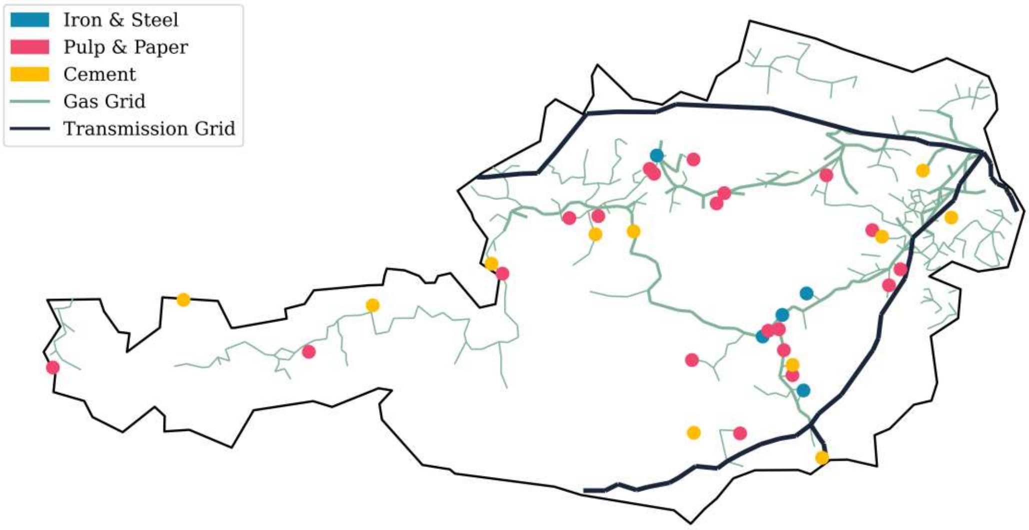

Figure 4.3: Network of the Austrian gas grid with the industrial sites of the IS, PP, and cement sector in 2040 in the scenario *Domestic Green Gases*

the *Electrification* scenario and are therefore assumed much lower in this scenario. The price of domestically produced renewable gases is considered to be even lower.Table 4.3 shows the energy carrier prices assumed for every five years to illustrate the influence of the energy carrier costs on the investment decisions into transition technologies. The prices are derived from (Schützenhofer et al., 2024) but altered according to the scenario. For example, the hydrogen price is lowered by 50 % to achieve some penetration of hydrogen in the transformation. In this scenario, domestically produced energy carriers are assumed to be grant-aided by the state, so domestic hydrogen only costs one-third of the imported hydrogen, and domestic green gases are 5 €/MWh cheaper.

The hydrogen grid expands from zero to 4864 km in 2040. Also, hydrogen production is increasing twice as much as in the other scenario from zero in 2020 to 5 TWh in 2030 and 14.3 TWh in 2040. The expected demand for hydrogen in this scenario is higher, and the costs for this energy carrier therefore lower. Again, domestically produced hydrogen is further promoted here and, therefore, even lower.

In this scenario, an additional case was analyzed, where the state is funding domestic hydrogen while obliging companies to consume this domestically produced hydrogen. This case is further described in section 5.2.4.

	2021 [€/MWh]	2025 [€/MWh]	2030 [€/MWh]	2035 [€/MWh]
Coal	20	20	20	20
NG / GG	40	35	30	25
Other fuels	17.5	17.5	17.5	17.5
Electricity	85	85	85	85
Hydrogen	100	70	55	50

Table 4.3: Energy carrier costs for the given five-year periods in the *Domestic Green Gases* scenario

5 Results

This section presents the calculated transformation pathways of Austria's IS, PP, and cement sectors. Thereby, the focus is put on the modeling results regarding the (i) installment of the different transition technologies in the industrial sites and the occurring costs for investments into transition technologies, (ii) energy carriers used, and (iii) CO_2 emissions. In addition, the use of different energy carriers in the sectors and their import ratio is shown, as well as the development of emission reduction and the pillars where the CO_2 is mitigated.

5.1 Transformation pathways in the "Electrification" scenario

The technological transformation pathways are analyzed separately for each sector, as the transition technologies are sector-specific. It is noted that the name of the scenario does not necessarily indicate a higher penetration of electricity in the industrial energy system but a lower electricity price and a lower penetration of green gases in the energy system.

Iron & Steel

The IS sector has five steel-producing locations, with three working on the secondary steel route and two working on the primary steel route with 5 BF installed. At the three production facilities processing scrap steel Marienhütte, Böhler Edelstahl, and Mittendorf Edelstahl, the installment of transition technologies of the pillars ELEC and FS are prohibited in the model because they already are using only EAF, which is the most energy-efficient form of steel production. In the results, no other transition technology is installed there, and there are not even energy efficiency improvements. In the two production sites from voestalpine, three different transition technologies are used in this scenario to mitigate emissions.

In 2022, 92 % of energy efficiency improvements are installed at voestalpine Linz and 77 % at voestalpine Donawitz, followed by CCS technologies being installed at both locations in 2026. A broader technological change is observed after 2030 when both BFs in Donawitz and one in Linz are replaced with DRI-NG, and EAF replaces the associated BOFs. Then, in 2032, the remaining two BF/BOF combinations at voestalpine Linz are replaced by DRI-NG with EAF. At the same time, because the optimization model does not allow negative emissions at a site, the energy efficiency improvements at voestalpine Linz are reduced to 77 %. This technological composition remains until the end of the observation period.

Pulp & Paper

The PP sector is treated in the optimization results as a homogeneous sector, and every transition technology is installed simultaneously in every industrial site. One of the reasons for this is that the SEC in the different sites does not vary due to a lack of more detailed data. In this sector, the lower electricity price affects the installation of transition technologies, as the main driver for emission reduction here is the heat pump and waste heat recovery, which will be installed at every site in 2025. The next and last transition technology installed in this sector is CCS in 2029 by 26 % in every site.

Cement

The most effective transition technology in the cement sector is CCS, which is the major one used for CO_2 emission reduction here. The sector is acting at the same time in every location, the same as the PP sector. In 2025, the CCS technology amine gas treatment will be installed in every cement site by 100 %, and at the same time, new binder materials will be used to improve clinker making. 5 % carbon calcium silicates and 5 % alkali activated binders are deployed.

5.1.1 Costs

The costs arising in the transformation pathway include the investment costs into transition technologies, costs for energy carriers, and costs for emitting CO_2 . The total costs in the scenario *Electrification* are 56.4 Bn€, table 5.1 shows the costs split up into the three terms and the sectors. The energy carrier costs are the most significant expense, which amount to 34.6 Bn€ over the 20-year period. This means that the costs for energy carriers are the main driver for technological transition, and lower prices for less CO_2 -intensive energy carriers are important. The IS sector has overall the highest costs, as it is the biggest industrial sector, especially seen in the CO_2 costs, which are 12 and 14 times higher than in the other two sectors. Also, the investment costs in the IS sector are more significant because the costs are a product with an annual production rate, which is very high in this sector. The energy efficiency improvements in the IS sector make up for 2.6 Bn€, CCS technology for 2.7 Bn€, and the DRI-NG/EAF cost 3.7 Bn€. In the PP sector, 0.8 Bn€ are invested in heat pumps, and the rest of the investment costs are invested in CCS technologies.

	Investment costs	Energy carrier costs	CO_2 costs
Iron & Steel	9 Bn €	18.6 Bn €	8.9 Bn €
Pulp & Paper	1.2 Bn €	12 Bn €	0.7 Bn €
Cement	1.3 Bn €	4.1 Bn €	0.6 Bn €
Total	11.4 Bn €	34.7 Bn €	10.3 Bn €

Table 5.1: Investment costs, energy carrier costs, and CO_2 costs during the observation period in the *Electrification* scenario

5.1.2 Energy consumption

In this scenario, the total energy demand is at 57.1 TWh at the beginning and 57.5 TWh at the end of the observation period. At the same time, the annual production in the IS sector increased slightly from 7.1 t_{Steel} in 2021 to 7.2 t_{Steel}[1], the production rate of the PP sector increased from 5.7 t_{Paper} to 5.8 t_{Paper} and the cement production increased from 5.2 t_{Cement} to 5.3 t_{Cement}. Figure 5.1 shows the energy demand in TWh split up by the sector and the energy carrier consumed every five years. In 2021, the total coal consumption was 23.3 TWh, NG consumption was 11.5 TWh, energy demand for other fuels like biomass was 12.3 TWh, and electricity demand was 9.9 TWh. At the end of the observation period, in 2040, the energy carrier demand was 2.1 TWh for coal, 28.7 TWh for renewable gases, 12.6 TWh for other fuels and 14 TWh for electricity.
One of the most illustrative transformations in figure 5.1 is the successive coal phase-out in the IS sector due to the installation of DRI furnaces in the two biggest production sites. The high annual production rate of about 1.8 t_{Steel} in only one furnace explains the big steps of the coal demand reduction. The demand reduction in 2025 is a result of the energy efficiency improvements implemented in the first years and the CCS technologies installed after 2025, which increased the energy demand again. However, the main driver of the energy carrier demand switch is the substitution of coal with NG and, later, with green gases.
The PP sector is using more energy-efficient heat pumps that reduce overall energy

[1] the annual production increase of all three sectors is assumed to be 0.1 %

demand on the one hand and substitute NG consumption with electricity demand on the other. Electricity demand in this sector increases from 5.5 TWh in 2021 to 9.2 TWh in 2040, and the total energy demand decreases from 21.3 TWh to 18.5 TWh. The installation of CCS in this sector also increases the total demand and reduces overall energy efficiency.
The cement sector has the highest relative demand increase of 41.2 % from 6.3 TWh in 2021 to 8.9 TWh in 2040. The energy demand growth of 40 % with the installment of amine gas treatment explains this effect, but a necessity for emission reduction in this sector.

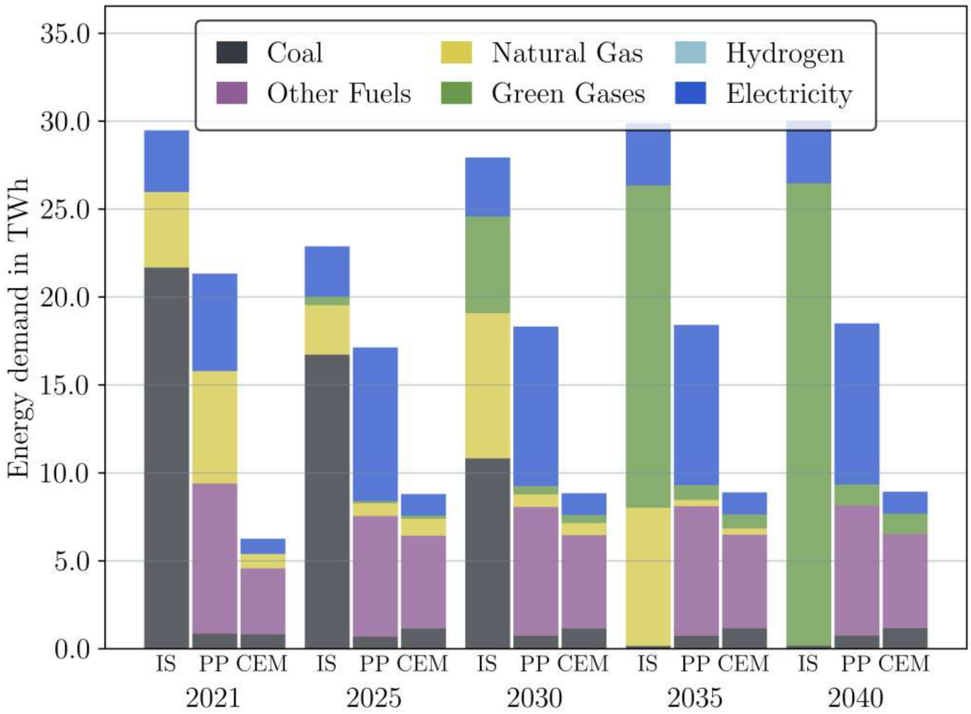

Figure 5.1: Energy carrier demand in the sectors IS, PP, and cement in the *Electrification* scenario

The origin of the energy carriers also plays a vital role in the future of industrial energy systems and is therefore considered in this calculation. Figure 5.2 shows the ratio of the imported energy carriers per total demand in the given years. The hashed part of the bars is the ratio of imported energy carriers. In 2021, the import ratio over every sector and energy carrier was 61 %, and it was reduced to 41 %. Some assumptions regarding the import ratio are important to note here: Coal and NG are fully imported, and electricity and other fuels like biomass are assumed to be 100 % from Austria. Only hydrogen and green gases are endogenous decisions, which stems from the definition of the scenarios. In this scenario, no hydrogen is used because the costs for this energy carrier are too high to enter the market. The import ratio of renewable gases in the first year they arise in 2030 is 37 % and in 2040, 74 % of the renewable gases need to be imported because in Austria only 7.4 TWh of it will be produced.

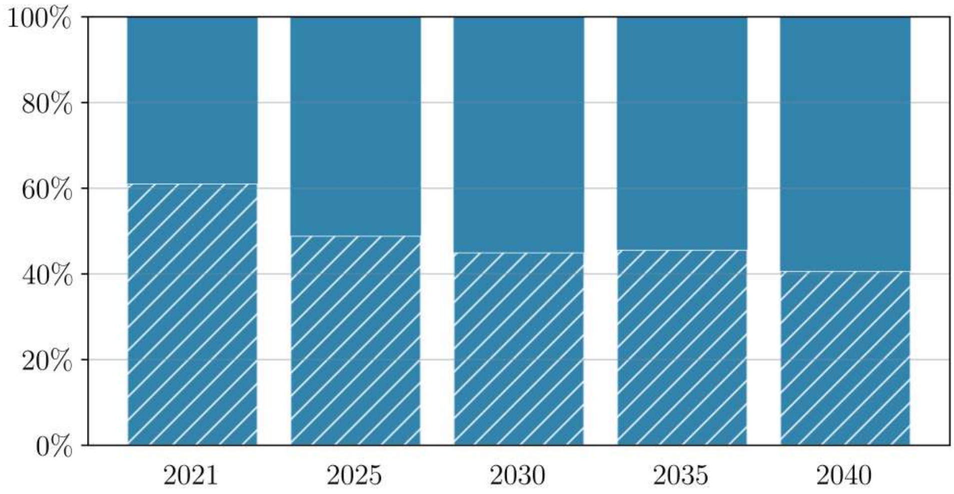

Figure 5.2: Import ratio of the consumed energy carriers in the *Electrification* scenario

5.1.3 Carbon emissions

To make the results for the transformation pathways more universally applicable, this section and the figure 5.3 deal with the reduction of the CO_2 emissions. In the figure, the total CO_2 emissions in the respective year are illustrated with the hashed bar, and the pillars of the transition technologies abating a certain amount of emissions are shown with the colored bars, filling up to the total CO_2 emissions that would arise without these technologies. The total emissions in 2021 are 16.5 $MtCO_2$. They are reduced to 10.6 $MtCO_2$ in 2025 by installing energy efficiency improvements in the IS sector, heat pumps in the PP sector, and CCS technologies in the cement sector. By 2030, CCS technologies will be installed in the IS and the PP sector and three DRIs in steel production sites, reducing emissions further to 4.1 $MtCO_2$. After that, the last measurement of replacing every BF/BOF in the IS sector is in 2032, leading to CO_2 emissions of 1.1 $MtCO_2$, which is the level of annual emissions for the remaining years. In total, 116 MtCO_2 are emitted throughout the 20 years, 80 % of this in the IS sector, and 10 % in each of the PP and the cement sector. Not 100 % of CO_2 emissions are mitigated because the transition technologies also have their limits. Transition technologies available in the short term are critical to reducing the total emitted CO_2 over the following years, even though they are not able to reduce the significant part of emissions. Technologies expected to be available later on will help achieve deep decarbonization of the industry in this scenario.

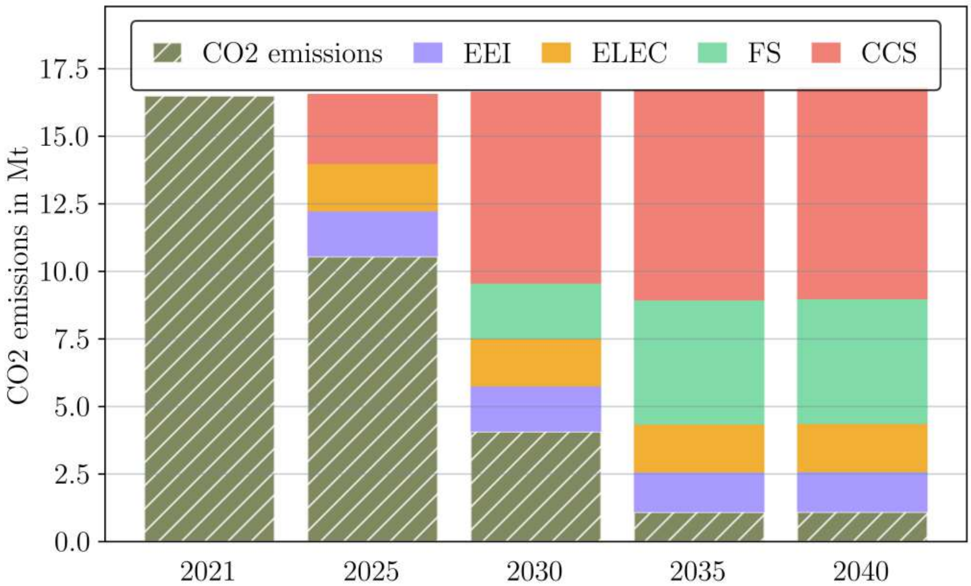

Figure 5.3: CO_2 emission reduction and the transition technology pillar mitigating the emissions in the *Electrification* scenario

5.2 Transformation pathways of the analyzed sectors in the scenario Domestic Green Gases

The parameters in this scenario promote renewable gases and hydrogen with lower costs for each energy carrier. Also, a higher domestic production of these energy carriers is assumed here.

Iron & Steel

In the *Domestic Green Gases* scenario in the IS sector, as well as in the *Electrification* scenario, no transition technologies are installed in the three sites on the secondary steel route, so all adjustments are made on the five BF/BOF combinations from voestalpine Linz and Donawitz. In 2022, energy efficiency improvements were installed by 77 % in Donawitz and by 56 % in Linz. Then, in 2025, the following transition technology installed is CCS, which is implemented by 100 % in Donawitz and by 73 % in Linz. In 2027, all BF/BOF combinations in Donawitz and two in Linz will be replaced by DRI-NG/EAF. The remaining blast furnace in Linz will be replaced in 2029 but with DRI powered by hydrogen, which might be promoted by the lower hydrogen price after 2030. After that, no additional steps are taken in the IS sector.

Pulp & Paper

The PP sector acts simultaneously in every site as well in this scenario. In 2022, 9 % of black liquor gasification is installed here in every site, followed by 100 % CCS technology in 2028. After that, no additional transition technology is implemented in this sector, and no electrification is carried out, as the electricity price is higher.

Cement

The cement sector's transformation pathway is similar to the *Electrification* scenario. Amine gas treatment will be installed at every cement production site in 2025 by 100 % to capture carbon emissions. Before that, in 2023, 10 % of new binder materials, alkali-activated binders, were used to improve the process.

5.2.1 Costs

Table 5.1 shows the investment costs, energy carrier costs, and the costs for CO_2 emissions in the *Domestic Green Gases* scenario with the total costs being 62.1 Bn €. In this scenario, the energy carrier costs stand out even more with 42.5 Bn € of which the IS and the PP sectors have only a small difference. The total costs in the IS sector are 35.1 Bn € with the smallest part here being the investment costs. Energy efficiency measurements in the IS sector cost 1.7 Bn €, CCS technologies 2.5 Bn € and investments into DRI/EAF amount to 2.3 Bn € for the NG-based technology and 0.9 Bn € for the hydrogen-based technology. In the PP sector, over the 20 years, total costs of 20.5 Bn € occur, the majority of the spending is for energy carriers. The investment costs are composed of investments into CCS technologies of 0.9 Bn € and the costs for black liquor gasification of 0.2 Bn €. The cement sector also has the most significant part of the costs for the energy carriers, the investment costs spent for CCS are 0.6 Bn € and for the technology for new binder materials 0.1 Bn €.

	Investment costs	Energy carrier costs	CO_2 costs
Iron & Steel	7.4 Bn €	19.7 Bn €	8.3 Bn €
Pulp & Paper	1.1 Bn €	18 Bn €	1.4 Bn €
Cement	0.7 Bn €	4.8 Bn €	0.7 Bn €
Total	9.2 Bn €	42.5 Bn €	10.4 Bn €

Table 5.2: Investment costs, energy carrier costs, and CO_2 costs during the observation period in the *Domestic Green Gases* scenario

5.2.2 Energy consumption

The total energy demand in the first year of the calculation in the *Domestic Green Gases* scenario is 57.1 TWh, figure 5.4 shows the annual energy carrier demand of each sector every five years. In 2021, coal demand amounts to 23.3 TWh, NG to 11.5 TWh, other fuels to 12.3 TWh and electricity demand is 9.9 TWh. The total energy demand increases to 63.2 TWh in 2040, 2.3 TWh of it being coal, 27.6 TWh green gases are consumed, 15.2 TWh other fuels, 12.7 TWh electricity and 5.4 TWh hydrogen. The annual production rates of the different sectors are the same as in the *Electrification* scenario, outlined in section 5.1.2.

The IS sector's demand for the different energy carriers changes drastically between 2025 and 2030 because every BF/BOF is replaced in this period by either NG- or hydrogen-powered steel production. The demand changes from 21.7 TWh coal, 4.3 TWh

NG and 3.5 TWh electricity in 2021 to 0.2 TWh coal, 11.3 TWh NG, 5 TWh electricity, 7.5 TWh green gases and 5.3 TWh hydrogen in 2030. In 2025, the energy demand does not change significantly because, although energy efficiency improvements are installed, CCS technologies that increase the specific demand are installed in 2025 as well. After 2030, the demand does not change significantly, except the consumption of NG is fully replaced by green gases. The total energy carrier demand in the PP sector increases from 21.3 TWh in 2021 to 24.7 TWh in 2040. Still, the composition of the energy carriers does not change significantly, except for the transition from NG to GG. In 2040, the energy carrier consumption in this sector is 1 TWh coal, 9.9 TWh other fuels like biomass or black liquor, 7.4 TWh GG and 6.4 TWh electricity. The demand increase in the cement sector is from 6.3 TWh in 2021 to 8.9 TWh in 2040, with the biggest part of consumption being other fuels with 5.4 TWh in 2040 and the rest of the energy carriers are consumed by more than 1 TWh each.

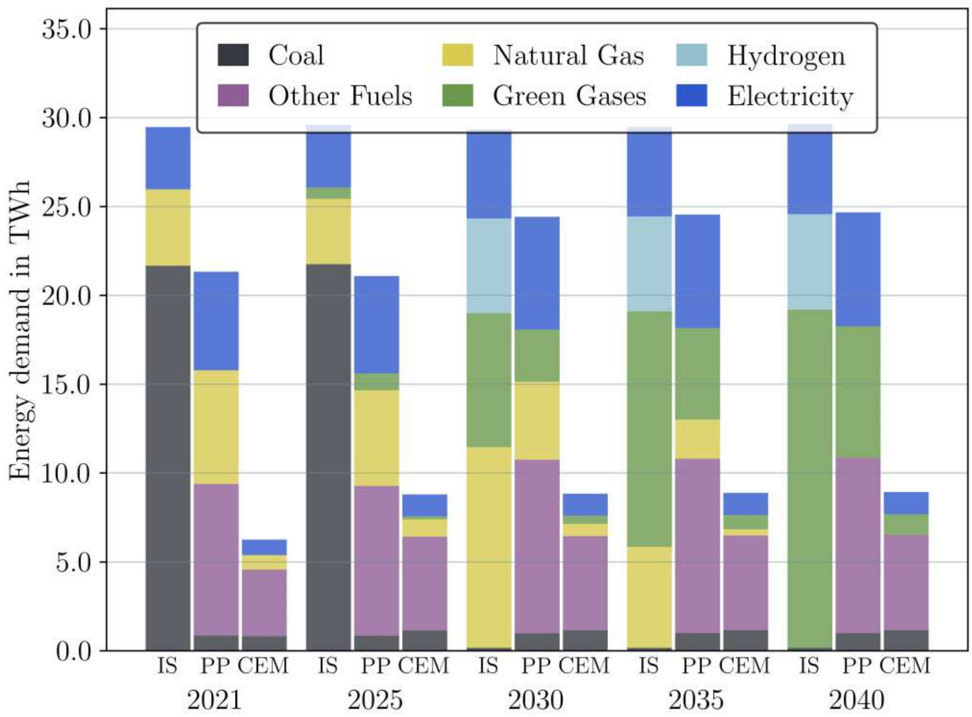

Figure 5.4: Energy carrier demand in the sectors IS, PP, and cement in the *Domestic Green Gases* scenario

In the *Domestic Green Gases* scenario, the import ratio of the different energy carriers depends only on the amount of import of the energy carriers' renewable gases and hydrogen. In this case, because the maximal hydrogen consumption is with 5.4 TWh much lower than the domestic available hydrogen, the import ratio of hydrogen is 0 % all the time. The most important energy carrier at the end of the observation period and, therefore, crucial for the overall import ratio is GG, accounting for 44 % of total energy demand. As shown in figure 5.5, the import ratio in this scenario sinks from 61 % to 16 % because most of the energy carriers used in 2040 are not imported. The import ratio of GG is at only 27 %. The total 20 TWh of domestically produced GG is consumed, and additionally, 7.6 TWh is imported.

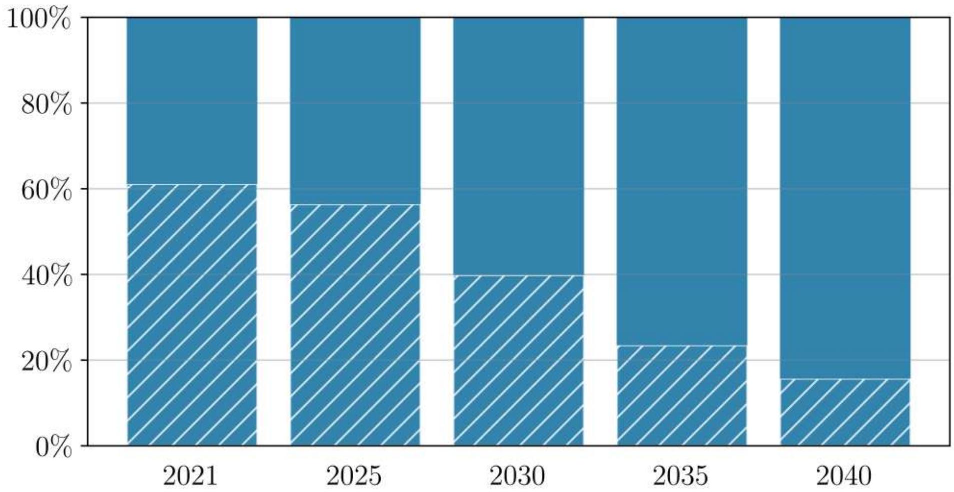

Figure 5.5: Import ratio of the consumed energy carriers in the *Domestic Green Gases* scenario

5.2.3 Carbon emissions

The CO_2 emission reduction will achieve its final value more or less in 2030 because no transition technologies are implemented. The carbon emissions in 2021 are 16.5 $MtCO_2$, reduced to 9.2 $MtCO_2$ in 2025, and in 2029, they reach 0.8 $MtCO_2$ emissions annually, and they remain at this level until the end of the observation period as portrayed in figure 5.6. The total emitted CO_2 in the three sectors during the 20 years amounts to 100 $MtCO_2$, 74 % of this in the IS sector, 16 % in the PP sector and 10 % in the cement sector.

In 2025, after installing energy efficiency improvements and CCS technologies, most of the decreased emissions will be captured in the IS and the cement sectors. As the coal-consuming blast furnaces are replaced between 2025 and 2030, a significant part of the carbon emissions will be mitigated because of the coal phase-out in the IS sector. Also, some CCS technologies are installed in the PP sector, resulting in more emission reduction due to CCS. In this scenario, no CO_2 is abated through electrification, but more through FS to either NG/GG or hydrogen.

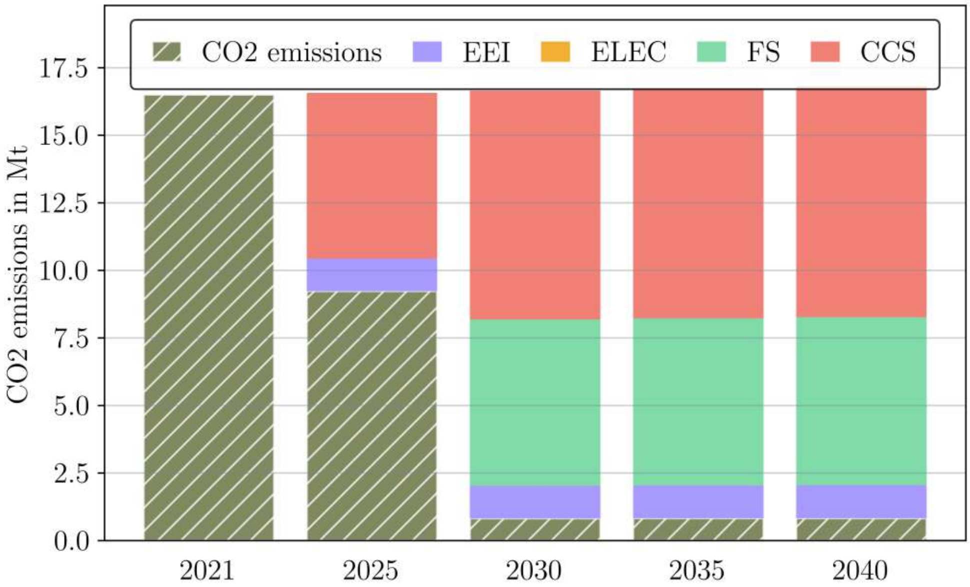

Figure 5.6: CO_2 emission reduction and the transition technology pillar mitigating the emissions in the *Domestic Green Gases* scenario

5.2.4 Case: Impact of obligation to consume domestically produced hydrogen

In this analyzed case, the input data is the same as in the standard *Domestic Green Gases* scenario. Still, a constraint 5.1 is included that obliges the industrial consumers to use domestically produced hydrogen.

$$\rho^{mix}_{y,c,m} \geq q^{max}_{y,c,m} \quad : \forall y, c = \text{"H}_2\text{"}, m = \text{"Domestic"} \tag{5.1}$$

The implementation of hydrogen affects only the technological transformation of the IS sector, so the PP and the cement sectors will not be described in this section. Nevertheless, for a better comparison, total costs, energy demand, and CO_2 emissions are explained for all sectors.

Transition technologies

In this case, energy efficiency improvements are installed by 77 % in Donawitz and by 36 % in Linz in 2022. and in 2025, CCS will be implemented by 100 % in Donawitz and by 46 % in Linz. In 2027, all BF/BOF combinations in Donawitz and one in Linz are replaced by DRI-NG/EAF. The remaining two blast furnaces will be replaced in 2029 by DRI-H_2. In 2040, the third steel-producing DRI in Linz is also replaced by a hydrogen-powered one because the value for the domestic production reaches the value given in table 4.1. At the same time, energy efficiency improvements at this site are reduced to 15 % and CCS is reduced to 19 % because emissions cannot be negative and the hydrogen-powered direct reduced iron is much less carbon-intensive.

Costs

The total costs in this case amount to 63.1 Bn € and are therefore only 1 Bn € higher than without the hydrogen obligation. CO_2 costs are the same as in the standard scenario. Energy carrier costs are higher because of the more expensive hydrogen, but investment costs are lower. That is because the costs for the DRI-H_2 are the same as for DRI-NG, but fewer other transition technologies are needed to achieve zero-emissions at the two regarding industrial sites because hydrogen-powered steel production itself emits less CO_2 than DRI-NG. So, the main barrier to higher penetration of hydrogen in the industrial energy system is not the technology itself but the cost of the energy carrier. Table 5.3 summarizes the costs for investment costs, energy carrier costs, and CO_2 emission costs for this case.

	Investment costs	Energy carrier costs	CO_2 costs
Iron & Steel	6.7 Bn €	21.4 Bn €	8.3 Bn €
Pulp & Paper	1.1 Bn €	18 Bn €	1.4 Bn €
Cement	0.7 Bn €	4.8 Bn €	0.7 Bn €
Total	8.5 Bn €	44.2 Bn €	10.4 Bn €

Table 5.3: Investment costs, energy carrier costs, and CO_2 costs during the observation period in the *Domestic Green Gases* scenario with the obligation of using domestically produced hydrogen

Energy consumption

Total energy demand in this case in 2021 is 57.1 TWh and increases to 62.4 TWh in 2040. As shown in figure 5.7, the energy demand and proportion of the different energy carriers in the PP and cement sectors is the same as in the standard *Domestic Green Gases* scenario. In 2040, the energy carrier demand is 2.3 TWh coal, 15.2 TWh other fuels, 15.7 TWh electricity, 13 TWh renewable gases and 16.1 TWh hydrogen, so hydrogen demand is about three times higher than without the obligation. The lower limit of hydrogen production in the last year is 14.3 TWh. Also, the demand for electricity demand is higher because hydrogen-based steel production needs more electricity.

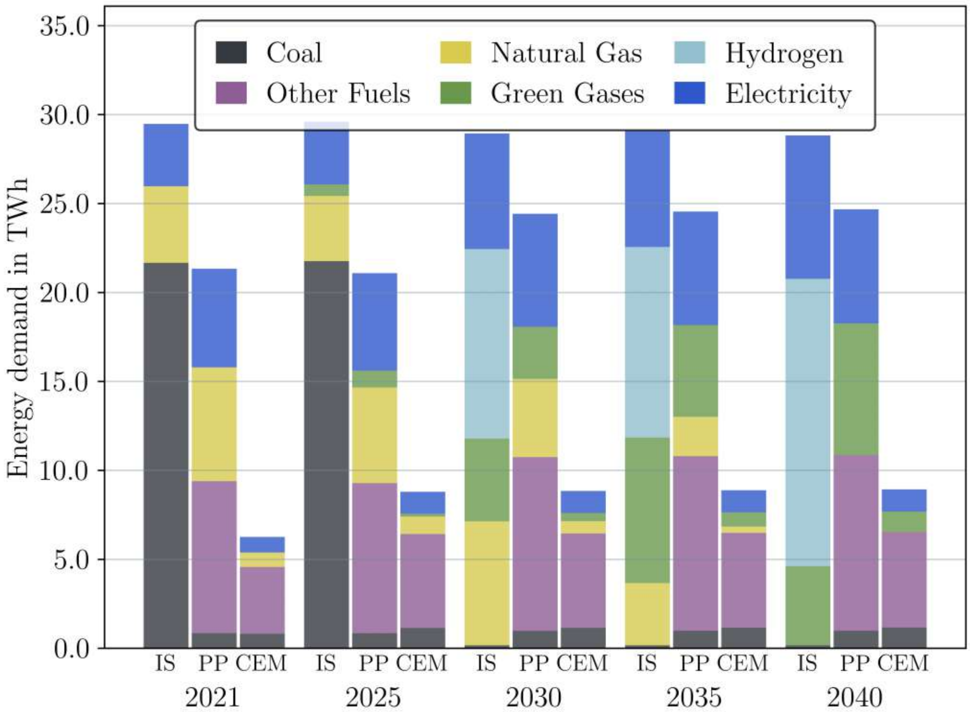

Figure 5.7: Energy carrier demand in the sectors IS, PP, and cement in the *Domestic Green Gases* scenario in the case of an obligation to consume domestic hydrogen

As hydrogen becomes more important in the IS sector, NG or GG demand decreases and is responsible for 20 % of the total energy demand in 2040 and is entirely domestically produced. Hydrogen takes up 25 % of total energy demand in 2040 and has an import ratio of 11 % because in the three installed DRI-H_2 more hydrogen is used than domestically produced. In total, the import ratio of the energy demand decreases drastically from 61 % in 2021 to 7 % in 2040, as shown in figure 5.9.

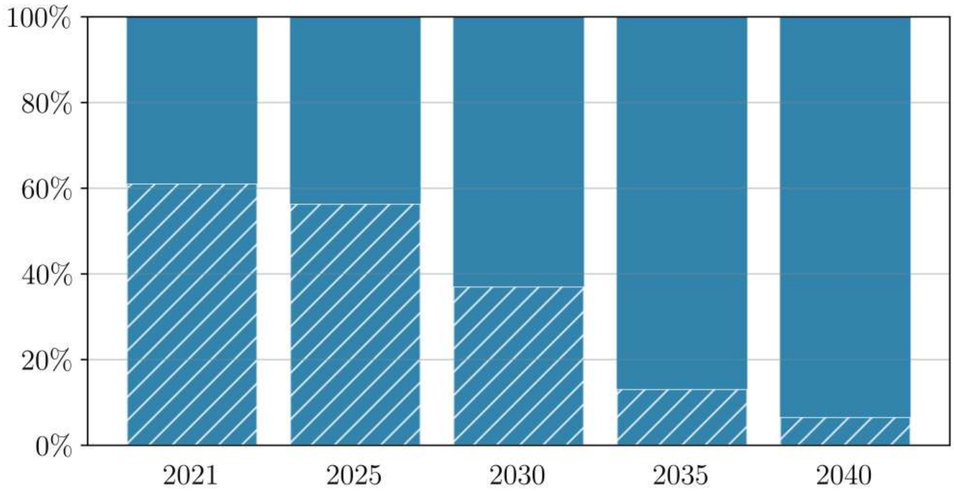

Figure 5.8: Import ratio of the consumed energy carriers in the *Domestic Green Gases* scenario in the case of an obligation to consume domestic hydrogen

Carbon emissions

The total CO_2 emissions during the 20 years amount to 105 $MtCO_2$ and are therefore higher than without the obligation. The additional 5 $MtCO_2$ occur solely in the voestalpine steel production site in Linz. As pictured in figure 5.9, energy efficiency improvements and CCS technologies are reducing the emissions less than in the standard scenario but more than the FS technologies, in that case, powered by hydrogen. So, the total amount of emissions is higher than in the standard scenario because, in the beginning, more CO_2 is emitted. Still, after the implementation of hydrogen-based technologies, the annual emissions are lower at 0.3 $MtCO_2$.

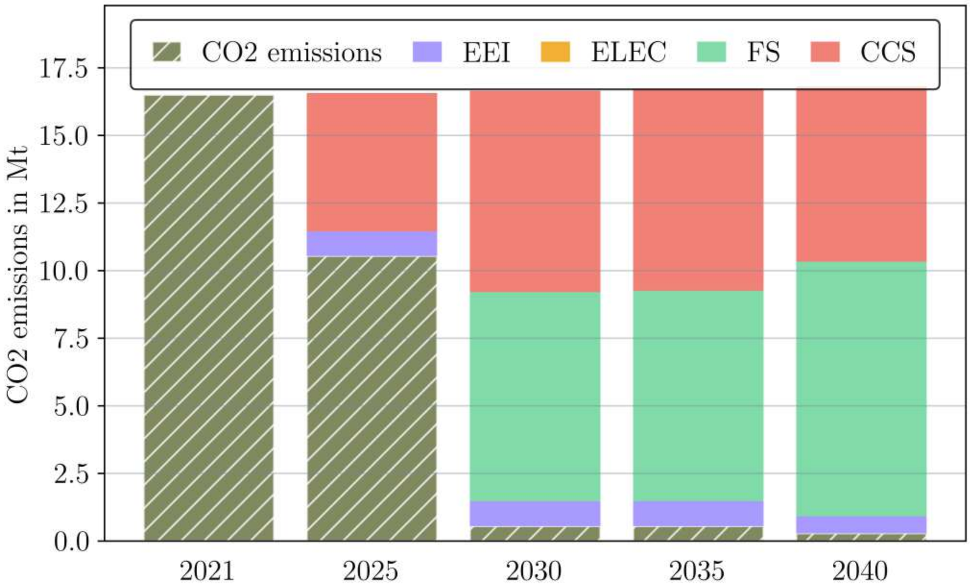

Figure 5.9: CO_2 emission reduction and the transition technology pillar mitigating the emissions in the *Domestic Green Gases* scenario in the case of an obligation to consume domestic hydrogen

5.3 Comparison of the scenarios

Overall, the transformation pathways in both scenarios lead to a well-decarbonized industrial energy system in the analyzed sectors with CO_2 emissions in the final year of 1.1 $MtCO_2$ in the *Electrification* scenario and 0.8 $MtCO_2$ in the *Domestic Green Gases* scenario. To compare the technological transition, the implemented decarbonization options at the end of the time horizon in the two scenarios are listed here, with the main differences being marked, beginning with the *Electrification* scenario:

- **Iron & Steel**:
  - **All five BF/BOF combinations are replaced by DRI-NG/EAF**
  - Energy efficiency improvements installed by 77 % in voestalpine Linz and Donawitz
  - CCS technologies installed at both sites
  - No transition technologies installed on the secondary steel-route
- **Pulp & Paper**:
  - **Heat pumps** for waste heat recovery installed at every site

  - CCS technologies installed by 26 % at every site
- **Cement**:
  - Amine gas treatment for carbon capture installed at every site
  - 10 % new binder materials to improve efficiency

Implemented decarbonization options at the end of the time horizon in the *Domestic Green Gases* scenario:

- **Iron & Steel**:
  - **Four BF/BOF combinations are replaced by DRI-NG/EAF and one in voestalpine Linz is replaced by DRI-H_2/EAF**
  - Energy efficiency improvements installed by 56 % in voestalpine Linz and by 77 % in voestalpine Donawitz
  - CCS technologies installed by 73 % in voestalpine Linz and by 100 % in voestalpine Donawitz
  - No transition technologies installed on the secondary steel-route
- **Pulp & Paper**:
  - **Black liquor gasification** is implemented by 9 % in every site
  - CCS technologies installed at every site
- **Cement**:
  - Amine gas treatment for carbon capture installed at every site
  - 10 % new binder materials to improve efficiency

In the *Electrification* scenario, the IS sector uses NG- or GG-based steel production to replace coal and electricity-powered heat pumps to decarbonize medium-temperature steam production. In the *Domestic Green Gases* scenario, the IS sector faces an earlier adoption of DRI, and parts of it are powered by NG/GG and parts by hydrogen, while the PP sector uses EEI technologies and CCS to decarbonize.

Table 5.4 shows the main quantitative differences in the results of the two scenarios. The total CO_2 emissions are higher in the *Electrification* scenario by 16 MtCO_2 . In the *Domestic Green Gases* scenario, fewer overall emissions are produced because hydrogen-based steel production is the less carbon-intensive option, but more emissions in the PP sector because electrification achieves more significant decarbonization in low- to medium-temperature applications. Both scenarios have similar results in the cement sector, using the same CCS technology and some new binder materials.

The total costs are smaller in the *Electrification* scenario with 56.4 Bn € than in the *Domestic Green Gases* scenario with 62.1 Bn €. Most of this difference comes from the higher energy carrier costs in the *Domestic Green Gases* scenario, on the one hand,

	Electrification	*Domestic Green Gases*
Investment costs	11.4 Bn €	9.2 Bn €
Energy carrier costs	34.7 Bn €	42.5 Bn €
CO_2 costs	10.3 Bn €	10.4 Bn €
Total costs	56.4 Bn € ↓	62.1 Bn € ↑
CO_2 emissions	116 $MtCO_2$ ↑	100 $MtCO_2$ ↓

Table 5.4: Comparison of the costs and the CO_2 emissions in the scenarios *Electrification* and *Domestic Green Gases*

because of the use of hydrogen and the higher electricity price, and on the other, because the energy demand in this scenario is higher, mostly in the PP sector. Nevertheless, the investment costs in the *Domestic Green Gases* scenario are smaller because fewer investments into the IS sector are needed. The decarbonization of the industrial sites in the IS sector needs fewer additional transition technologies because the DRI-H_2 already decarbonizes more.

6 Conclusion

For assessing the industry's transformation pathways until 2040, a techno-economic optimization model, carried out as a MILP, is introduced in order to find cost-optimal technology portfolios. A set of transition technologies for decarbonizing industrial processes is considered, altering the specific energy carrier demand and specific CO_2 emissions and thus changing the operational costs. The proposed bottom-up approach for the implementation decisions of those transition technologies proved to be a sufficient method for answering the presented research questions. The answer to the first research question is outlined through the calculated transformation pathways and is determined by the investment decisions into the transition technologies. The second research question, regarding the network infrastructure, analyzes the influence of top-down given energy system parameters on the optimization results.

The results show that short-term options need to be explored for rapid mitigation of CO_2 in the industry. These technologies must be already commercially available and easily implemented in the current processes. Two pillars of transition technologies are implemented in the early phase of the pathways in most industrial sites, energy efficiency improvements and carbon capture. The effect of energy efficiency measures can be seen in the results for carbon mitigation and show that these technologies, although the effect seems less significant compared to CCS, have an essential impact on the total CO_2 emissions throughout the observation period. This indicates that these "low-hanging" fruits are worth their investments because they help to decarbonize the system fast. The importance of CCS can be seen mostly in hard-to-abate sectors, where sometimes the only possibility for deep decarbonization is carbon capture. The amount of CO_2 emissions captured every year (about 8.5 $MtCO_2$ in the *Electrification* scenario in 2040) elucidates the importance of possibilities for the utilization or transport of the captured carbon. Solutions to further process and distribute carbon emissions are critical when exploring carbon capture.

A long-lasting decarbonization of the industry can only be achieved by replacing fossil fuels with sustainable carbon-neutral options. The electrification of industrial processes is estimated to be one of the main ways the sector will operate. In this work, the increasing importance of electricity in the industry can be seen only in parts, but it is still significant. Low- to medium-temperature heat or steam applications used in the PP sector are suitable for electrification but not yet high-temperature process heat generation, which is the main energy consumer in the analyzed sectors. Another example of the need for fossil fuel substitution can be seen in the results of the IS sector, where a coal phase-out is accomplished by using new technologies to reduce the iron for further steel production with NG, GG, or hydrogen. These renewable gases will be the biggest energy carrier used in the analyzed sectors.

The (IS) industry uses hydrogen for decarbonizing the processes only if the price is very low. The costs for energy carriers are the main levers to steer the direction of the transformation pathways, as the energy carrier costs are the critical cost term of the results. The costs and the cost-stability for renewable gases or hydrogen depend on the availability of the respective energy network infrastructure on the one hand and the diversification of the sources of the energy carrier on the other. So, the availability and economic profitability of renewable gases and hydrogen in the future, not only in the Austrian energy system but also in the locations of the spatially distributed consumers, plays a vital role in industrial decarbonization. This calls for regulatory frameworks to fund the generation and distribution of sustainable energy carriers like hydrogen to make it economically competitive against fossil fuels or other energy carriers. Also, as we have seen in the past, the reliance on third countries for fuel supply in the EU needs to be prevented upfront to ensure steady prices for industrial energy consumption and, therefore, the competitiveness of the EU's industry.

One of the limitations of the proposed approach is the detail of the considered processes that could be further enhanced. More precise statements about altering the specific energy demand and CO_2 emissions could improve the model's accuracy. The challenge for this modification of the model is the data acquisition for the industrial sites and the transition technologies. Still, they would positively impact the optimization and the diversification of the results for the different locations. Another limitation is the differentiation between NG and GG, which is made only with an exogenous parameter but could be considered an endogenous decision of the model with some adjustments.

The structure of the implemented model makes it easy to expand the model to more industrial subsectors, which is a crucial part of future work. In accordance with the current limitations of the model, process details could be improved in the future, not only to diversify the industrial landscape but also to include material flows. This could help contain the fifth pillar of transition technologies, the circular economy. Recycling materials will significantly impact industrial decarbonization in the future and is, therefore, very interesting to explore. Furthermore, increasingly precise statements about the transport of materials and CO_2 could be included to analyze carbon sinks in other sectors and explore the coupling between industrial subsectors.

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