THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Electrification of the basic materials industry
– Implications for the electricity system

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Gothenburg, Sweden 2023

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ISBN 978-91-7905-824-1

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 5290
ISSN 0346-718X

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Printed by Chalmers Reproservice
Gothenburg, Sweden 2023

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Abstract

The European energy-intensive basic materials industry must achieve deep reductions in CO_2 emissions to meet the targets set out in the Paris Agreement. The rapid decline in the cost of renewable electricity makes expanded electrification an attractive option for eliminating the dependence of the industry on fossil fuels.

This work applies techno-economic optimisation modelling to investigate how electrification of the basic material intensive industry in EU can interact with the electricity system. In particular, this work examines the ability of basic material industry to take advantage of flexibility options in the production processes to avoid high-cost electricity and facilitate the integration of wind and solar power. The thesis considers flexibility options which can meet an uneven distribution of electricity in time and space, including options to invest in overcapacity in electrolysers for hydrogen production and storage (flexibility in time) and the ability to export commodities (flexibility in location) for the industries included (ammonia, cement, plastics, and steel). For the electrified process of plastics production, flexibility in terms of CO_2 utilisation is used to describe the ability of industrial units to vary their CO_2 utilisation modes, i.e., through carbon capture and utilisation and carbon capture and storage.

The modelling results show that an energy-intensive basic materials industry that has flexibility in relation to time, location, and CO_2 utilisation provides lower production costs compared to a non-flexible industry. This is despite the lower capacity utilisation rate (60%) of the electrolysers used for hydrogen production, i.e., it is cost-efficient with investment in over-capacity in electrolysers.

The modelling results also show that availability of low-cost electricity generation is the main determining parameter for geographical location of new industries with high operational flexibility and high hydrogen intensity (in this work presented by ammonia industry). With present-day locations of the industry, a hydrogen pipelines network allows for moving the electrolyser capacity from industry-intensive regions to regions with access to low-cost electricity which reduces hydrogen production costs by 3%. With the modelled optimal geographical location of new industries, hydrogen production is in the same region as the hydrogen-consuming units and, thus, a hydrogen pipeline has no significant impact on the hydrogen production cost.

It was found that the electrification of the energy-intensive basic materials industry in the EU increases the electricity demand by around 44% (by 1,200 TWh). The future EU electricity demand with the present-day locations of the industrial plants is primarily met by solar, wind and nuclear power. If changes in annual production volumes and relocation of industries are allowed, more commodities are produced in regions that have both existing industries and access to low-cost electricity, thereby increasing the levels of electricity generation from wind and solar power. All the modelled scenarios require a substantial and rapid increases in renewable electricity capacity.

Keywords: electrification, electricity systems modeling, storage, flexibility, circular economy, industry, hydrogen, renewables

List of publications

The thesis is based on the following appended papers, which are referred to in the text by their assigned Roman numerals:

I. Toktarova, A., Karlsson, I., Rootzén, J., Göransson, L., Odenberger, M., & Johnsson, F. (2020). Pathways for low-carbon transition of the steel industry—a Swedish case study. *Energies*, *13*(15), 3840.

II. Toktarova, A., Göransson, L., & Johnsson, F. (2021). Design of clean steel production with hydrogen: Impact of electricity system composition. Energies, 14(24), 8349.

III. Toktarova, A., Walter, V., Göransson, L., & Johnsson, F. (2022). Interaction between electrified steel production and the north European electricity system. Applied Energy, 310, 118584.

IV. Toktarova, A., Göransson, L., Thunman, H., & Johnsson, F. (2022). Thermochemical recycling of plastics–Modeling the implications for the electricity system. Journal of Cleaner Production, 374, 133891.

V. Toktarova, A., Göransson, L., & Johnsson, F. (2022). Electrification of the energy-intensive basic materials industry – Implications for the European electricity system. Submitted for publication to Renewable and Sustainable Energy Reviews.

Alla Toktarova is the principal author of all papers. Professor Filip Johnsson contributed with discussion and editing of all papers. Associate professor Lisa Göransson contributed to the method development in **Papers II-V**, as well as with editing and discussion for all papers. Ida Karlsson, Dr. Johan Rootzén and Associate professor Mikael Odenberger contributed with reviewing and discussion of **Paper I**. Dr. Viktor Walter contributed with modelling and discussion of **Paper III**. Professor Henrik Thunman contributed with method development, editing and discussion of **Paper IV**.

Other publications by the author, not included in the thesis:

A. Toktarova, A., Karlsson, I., Rootzén, J., & Odenberger, M. (2020). Technical Roadmap Steel Industry. Mistra Carbon Exit: Stockholm, Sweden.

B. Karlsson, I., Rootzén, J., Toktarova, A., Odenberger, M., Johnsson, F., & Göransson, L. (2020). Roadmap for decarbonization of the building and construction industry—A supply chain analysis including primary production of steel and cement. Energies, 13(16), 4136.

C. Karlsson, I., Toktarova, A., Rootzén, J., & Odenberger, M. (2020). Technical Roadmap Cement Industry. Mistra Carbon Exit: Stockholm, Sweden.

D. Karlsson, I., Toktarova, A., Rootzén, J., & Odenberger, M. (2020). Buildings and transport infrastructure: technical roadmap. Mistra Carbon Exit: Stockholm, Sweden.

E. Lehtveer, M., Göransson, L., Heinisch, V., Johnsson, F., Karlsson, I., Nyholm, E., & Walter, V. (2021). Actuating the European Energy System Transition: Indicators for Translating Energy Systems Modelling Results into Policy-Making. Frontiers in Energy Research.

Acknowledgments

Between February 2018 and March 2023, in my personal view, three significant historical events occurred - namely, the Trump presidency, the global pandemic, and the invasion of Ukraine. What a time. Despite the challenges posed by these events, I was fortunate enough to have received the support and assistance of many individuals who made my PhD adventure possible. For helping me navigate the ups and downs of this PhD journey, I would like to thank my supervisors Filip Johnsson and Lisa Göransson. Filip, thank you for your guidance and support along the way. Your impressive ability to keep pace with the time and be always on the spot is a great inspiration for me. Also thank you for helping me to always fulfill the toughest deadlines ever. Lisa, thank you for providing great support in untangling complex knots in research and life, and for helping me develop critical thinking skills in problem-solving. Your guidance has been essential in helping me strike a balance between structure and creativity.

Mikael Odenberger, thank you for introducing me to the "fast and furious" approach to work that I now find indispensable. Johan Rootzén, thank you for always providing valuable insights and sharing your knowledge with me. Ida Karlsson, thank you for being my office mate and bringing your infectious laughter to the workplace. Thank you, Viktor Walter, for showing by your example how to enjoy research no matter what. Your curiosity and lust for knowledge are great inspirations to me. Thank you, my teaching partners - Jonathan Ullmark and Henrik Hodel, I enjoyed creating and developing new things together. Also thank you Jonathan for teaching me how to read "the code". Thank for energy systems modeling group for all the interesting meetings, presentations, workshops, and discussions, which allowed me to develop as a researcher and to learn something new.

Thank you to the gasification group for your valuable assistance in the writing of Paper IV. Your willingness to collaborate and share your expertise made the process enjoyable and productive. Special thanks to Henrik Thunman, Chahat Mandviwala, Tharun Roshan Kumar, Isabel Cañete Vela, Teresa Berdugo Vilches, and Martin Seemann. Thank you, fluidization group, specially to Guillermo Juan Martinez Castilla, Diana Carolina Guío-Pérez, Javier Cortès Romea and David Pallarès, for the energy you brought into my life and help in the developing my leadership skills. Thank you, Carolina, for helping me to find my loud voice, your inexhaustible energy is truly inspiring and empowering. Thank you, Guillermo, for introducing the work-life balance and words "beautiful" and "amazing" into my life. Thank you, Maria de Oliveira Loureiro and Hyunkyo Yu, for keeping me from becoming a fault-finding, cynical, and jaded PhD student. Your positivity and strength have had a refreshing influence on me. I would also like to thank Marie Iwanow and Katarina Bergkvist for always providing a supportive environment and the necessary resources for productive work in the division. Thank you for all my present and former colleagues at the Division of Energy Technology for a fun working environment and countless moments of fika. To future PhD students at the Energy Technology division if you, like me, only read the acknowledgements in the thesis, this message is to you, enjoy this journey (while you can). Thank you, Vincent Collins, for reading my papers and tolerating me not knowing English articles. Thank you, Mistra Carbon Exit Research programme for making this work, possible and especially to Lars Zetterberg, it is great pleasure working with you.

Thank you, to my friends all around the world, for your unwavering support, love, and warmth, even though we are in some cases separated by many kilometers. Finally, thanks to my parents (Ruslan and Lydmila), for your encouragement and love. By the way I don't study maths at uni anymore. My special thanks to my beloved grandmother for always being my role model in being a powerful and smartest woman in this world.

Göteborg, 22nd of March 2023

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1 Introduction

Tackling climate change and minimising its effects are on the agendas of governments world-wide. Based on the goals of the Paris Agreement (2015), stabilisation of the increase in global average surface temperature to well below 2°C requires that global carbon emissions reach net zero and possibly become negative sometime between 2055 and 2080 [1]. To date, 57 countries have formulated and submitted long-term, low-level greenhouse gas (GHG) emissions development strategies [2]. To achieve the climate neutrality objective, it is obvious that all sectors must contribute to drastically reducing fossil-fuel carbon emissions and also removing carbon emissions from the atmosphere (establishing "negative emissions"), so as to compensate for residual emissions in "hard-to-abate" sectors.

In Europe, industry is responsible for over 24% of the total CO_2 emissions [3]. There are significant differences between the different types of industries in terms of energy consumption and CO_2 emissions. In Year 2020, the steel, cement, chemical, and petrochemical industries, typically referred to as the energy-intensive industries (EIIs), were responsible for 70% of industrial CO_2 emissions globally [4] (Figure 1.1). These industries are embedded in many strategic value chains and account for more than half of the energy consumption of industry in the European Union (EU) [5].

In December 2019, the European Green Deal was introduced by the European Commission (EC). The aim of this development strategy is to achieve net-zero GHG emissions in the EU by Year 2050 [7]. In March 2020, a new industrial strategy for Europe was released by the EC. The importance of industry for the transformation toward a carbon-neutral economy is recognized in this strategy [8]. In 2020, the COVID-19 pandemic shocked the global economy and spurred economic incentives for green recovery [9]. In 2021, the EC presented the 'Fit for 55' package [10]. The purpose of the package is the implementation of the EU's Green Deal, which entails a 55% reduction in GHGs by Year 2030, as compared with Year 1990, and making the EU climate-neutral by Year 2050. The European security situation has been significantly changed by Russia's invasion of Ukraine in 2022. This will have impacts on the European economy, as well as on the movement of European economies towards climate neutrality [11].

To achieve a 55% reduction in GHGs by Year 2030, decarbonisation of EIIs is critical. However, the long-lived capital stocks, high-temperature heat requirements, the presence of process emissions, and global trade in commodities make it challenging to mitigate emissions from EIIs [12,13]. Applying the best-available technologies (BATs) is estimated to reduce industrial emissions by only 15%–30%, even if they are applied on a large scale [14]. Energy efficiency improvements are low-hanging fruits and can provide emissions reductions already in the near term [15]. Meeting long-term mitigation targets requires major efforts to develop, introduce and invest in new “break-through technologies” [16]. Break-through innovations enable the replacement of fossil fuels with electricity, hydrogen, and biomass, the replacement of feedstocks, and the integration of CO_2 emissions capture (CCS) into the process design [17].

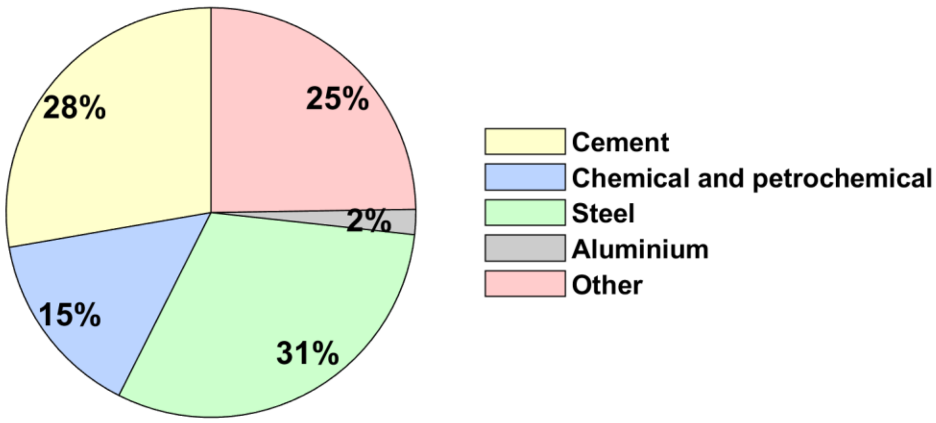


Figure 1.1: Shares of global CO_2 emissions from industry in Year 2020. The total emissions amounted to roughly 8.8 $GtCO_2$ [6].

The electricity generation sector is generally regarded as having the greatest potential for low-cost emissions reductions among the energy sectors, due to the availability of a number of low-carbon electricity generation technologies, such as electricity generation based on renewable energy sources (RES) in the form of wind, solar, hydropower and biomass, as well as the option to produce electricity from nuclear power. The substantial cost decrease and increased cost-competitiveness relative to both fossil-fuel and nuclear power make energy sources in the form of wind and solar, together with flexibility measures, a core climate change mitigation strategy. Of particular interest is that RES such as wind and solar power have shorter lead times for building than nuclear power [18]. Yet, large shares of variable renewable electricity (VRE) [1] will cause regular and irregular variations in the electricity supply, which will occur on different time-scales, creating challenges associated with utilising VRE for meeting the demand [19].

For electrified EIIs, it is important to investigate the costs for varying the load and switching operation modes according to the availability of wind and solar power, to determine if these

[1] This work assumes that variable renewable electricity (VRE) is from wind and solar power.

activities are cost-beneficial [20]. The electrification of industry can significantly change the cost structures for industrial production and, thereby, the most-cost-effective geographical locations for new production sites. With the objective of zero emissions production, the optimal location for production may shift from being close to the demand and/or the raw material supply centres to sites where zero-emissions electricity is readily available at low cost, or where there are favourable conditions for CCS [21].

1.1 Aim and scope

The overall aim of this thesis is to investigate the interactions between the electricity system and an electrified energy-intensive basic materials industry. The work takes its departure from future energy systems with net-zero CO_2 emissions and, consequently, with large shares of renewable electricity generation in the forms of wind and solar power. The analysis is time-resolved, taking into consideration different flexibility options for the production processes. The work of this thesis spans investigations at different levels, from dedicated analyses of how to electrify a specific industry at the national level to the impacts of large-scale electrification of energy-intensive basic materials industry at a multi-national level. The research questions addressed in this thesis can be summarised as follows:

i. What roles do different CO_2 abatement technologies play in reducing the emissions from industry, and when in time it is reasonable to assume that these technologies can be implemented?

ii. How does the electrification of industry influence the costs of the produced commodities and the sizing and production levels of the electrified industry when considering flexibility options for the electrified industry?

iii. Which parameters determine the spatial distribution of electrified industry that yields the lowest cost?

iv. Which electricity generation technologies meet the potential future electricity and hydrogen demands from industry and how do these technologies depend on the flexibility of the demand?

These four objectives form the basis for **Papers I–V**, which are appended to this thesis. The methods applied in this work are a techno-economic pathways concept (**Paper I**) and techno-economic optimisation models (**Papers II–V**).

Paper I investigates the transition of the Swedish steel industry to zero-emissions steel production with a 1-year temporal resolution from 2020 to 2045. The temporal scope of **Papers II–V** is a future year (around Year 2050 if complying with the Paris Agreement), modelled with a chronological 1-hour resolution in **Paper II** and with a 12-hour resolution in **Paper III**. In **Papers IV** and **V**, 730 chronological time periods are applied. The work applies different geographical scopes. In **Paper II**, the geographical scope of the modelling includes two European countries/regions, Scotland and Southern Germany, to capture the different conditions for generation from wind and solar power. The geographical scope is further expanded in **Papers III** and **IV** to cover Northern Europe, and in **Paper V** to cover the EU. Table 1.1 provides a summary of **Papers I–V**, including the time and geographical scopes, and the sectors and their flexibility options, as applied in the appended papers.

Table 1.1: Summary of the scopes of the studies described in the appended papers, including the modelling dimensions.

	Paper I	**Paper II**	**Paper III**	**Paper IV**	**Paper V**
Title of paper	Pathways for low-carbon transition of the steel industry—a Swedish case study.	Design of clean steel production with hydrogen: Impact of electricity system composition.	Interaction between electrified steel production and the north European electricity system.	Thermochemical recycling of plastics – Modelling the implications for the electricity system.	Electrification of the energy-intensive basic materials industry – Implications for the European electricity system.
Focus of paper - sectors	Steel industry	Steel industry	Steel industry and electricity system	Plastics industry and electricity system	Ammonia, cement, steel, plastics industries, and electricity system
Flexibility options of industry	Flexibility in location: export of HBI.	Flexibility in time: storage of HBI, flexible operation of steel production capacity and hydrogen storage	Flexibility in time: storage of HBI, flexible operation of steel production capacity and hydrogen storage; Flexibility in location: export of iron ore, HBI and steel.	Flexibility in time: storage of methanol, flexible operation of plastics production capacity and hydrogen storage; Flexibility in location: export of waste, plastics waste, methanol and plastics; Flexibility in CO_2 utilisation: CCS or/and CCU.	Flexibility in time: storage of commodities and flexible operation of industrial units; Flexibility in location: export of commodities and hydrogen; Flexibility in CO_2 utilisation: CCS or/and CCU.
Time period	Yearly, from 2020 to 2045	Hourly for one year*	Twelve-hourly for one year*	730 consecutive time-steps of one year*	730 consecutive time-steps of one year*
Geographical regions	Sweden	Southern Germany and Scotland	Northern Europe	Northern Europe	EU

* Around Year 2050 if complying with the Paris Agreement

1.2 Contents of papers in the thesis

The objectives listed in Section 1.1 are addressed in the appended papers, which are summarised below.

Paper I analyses the extent to which CO_2 abatement measures can reduce emissions from steel production if combined to maximise their potential based on an implementation timeline that is linked to their technical maturity and to the age structure of the existing capital stock for the case study of the Swedish steel industry.

In **Paper II**, a model is developed to study how electricity price variations affect the steel production capacities that apply to the H-DR steel production process in terms of: (i) investments; and (ii) the operational times and operational levels of the steel production capacities, including storage utilisation. This work adds to the existing research on energy systems by analysing the flexibility in time of industry (i.e., storage of HBI pellets, flexible operation of steel production capacity and hydrogen storage) to meet electricity price variations. In **Paper II**, the electricity price is applied exogenously in the model, which means that the response of the electricity system to the new demand for electricity from the steel industry is missing. The modelling work conducted in **Paper II** is further developed in **Paper III**.

In **Papers III-V**, an existing electricity system model is utilised and complemented with equations, variables, and parameters to represent the electricity demand from electrified industries.

Paper III describes how electrified steel production can influence: (i) the geographical location of new steel plants and their sizing; (ii) the investment decisions related to new electricity generation capacity; and (iii) the commodity trade flows between the regions investigated. The inclusion of an electricity system feedback on the introduction of electrified industry (considering flexibility options) is considered to be the main modelling contribution of this work, in that it fills a gap in the literature. Flexibility options for the industry, including flexibility in time and flexibility in location (i.e., the ability to export commodities), are considered in this work.

Paper IV investigates the interactions between the electricity system and electrified production of plastics (thermochemical plastic recycling and waste gasification), taking into consideration the different flexibility options (flexibility in time, flexibility in location, and flexibility in CO_2 utilisation) for the plastics production processes.

Paper V evaluates the impact of electrification of energy-intensive industries on investments in and operation of the European electricity system, as well as on the spatial distribution of future industrial plants and their production levels. The context of the work is a zero-carbon emissions energy system, including future electricity demands from transport, heat, and industry. **Paper V** refines and improves upon previous modelling studies (**Papers III** and **IV**) by considering the combined effects of electrified energy-intensive industries on the electricity system.

Figure 1.2 presents a graphical overview of the relationships between the appended **Papers I–V**, indicating which sectors are investigated in each paper and which flexibility options for the industry are considered, i.e., flexibility in time, flexibility in location, and flexibility in CO_2 utilisation.

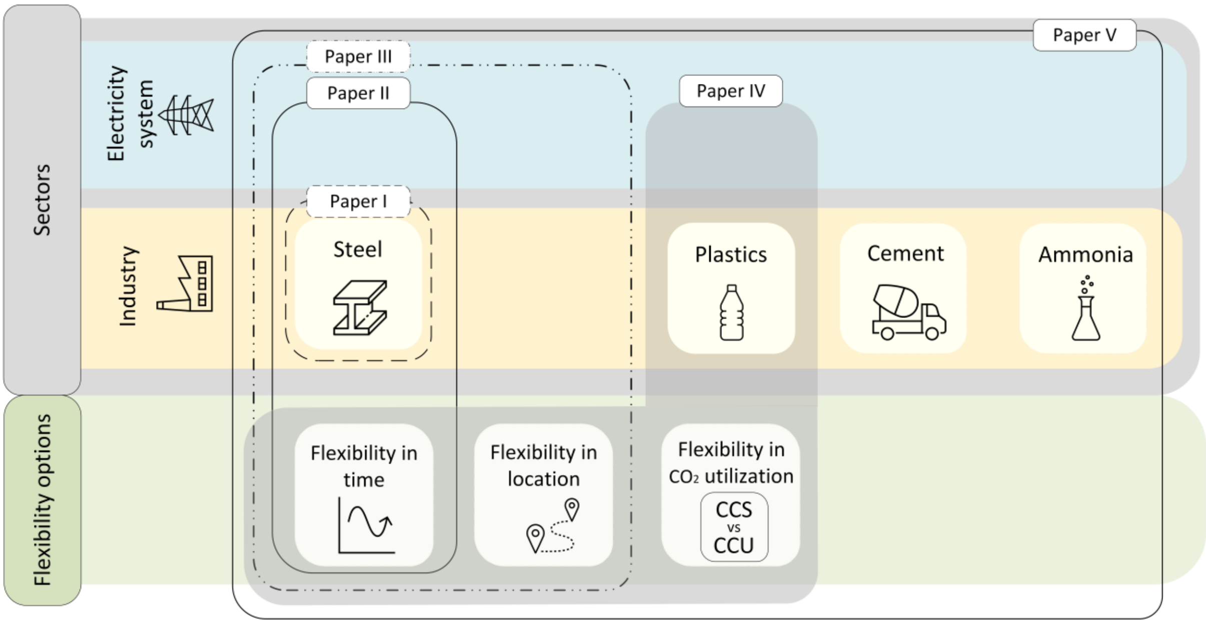


Figure 1.2: Overview of the areas explored in this thesis and the relationships between the research topics of the appended papers.

1.3 Outline

This thesis consists of an introductory essay and five appended papers. The introductory essay places the work in context and summarises the findings of the appended papers. Chapter 2 provides the background to the research field. The methodology of the work is presented in Chapter 3. The main results from the appended papers are summarised in Chapter 4, and a discussion of the work is presented in Chapter 5. Finally, concluding remarks and recommendations for future work are presented in Chapter 6.

2 Background and related work

The following chapter describes the key characteristics of the basic materials industry – ammonia, cement, steel, and plastics industry. Section 2.1 aims at framing the industrial decarbonisation challenge. Section 2.2 briefly describes key CO_2 emission reduction measures. Section 2.3 gives a detailed description of the assumed electrification options for the basic materials industries investigated in this study. Section 2.4 describes three flexibility options for the electrified industries. The main characteristics of future electricity systems are given in Section 2.5, which also briefly explains variations related to wind power and solar power. Section 2.6 presents related work on electrification of the basic materials industries.

2.1 Basic materials industry – overview

The production, use and, consumption of basic materials has been the backbone of modern society over the last century. The production of basic materials such as ammonia, cement, steel, and plastics stands for the major share of industrial emissions (70% of European industrial CO_2 emissions in 2020, Figure 1.1) including energy and process-related emissions.

Figure 2.1 indicates that production of 1 tonne of steel results in a total of 1.8 tonne of direct CO_2 emissions [22,23], of which about 40% can be linked to the process reaction [24]. For every tonne of cement that is produced, around 0.7 tonnes of CO_2 (tCO_2) are released into the air, of which 0.47 tCO_2 are process-related [25,26]. For cement, emissions depend on the clinker to cement ratio. The benchmark used by the EU is a clinker-to-cement ratio of 73.7%. Plastics production accounts for 4.6 tCO_2 per tonne of plastics [27]. The term plastics refers to a variety of materials, with different properties and end uses. The five polymer types (PE, PP, PS/EPS, PVC, and PET) account for some 75% of the use [28]. Ammonia production has an average CO_2 emission footprint of 2.4 tCO_2 per 1 tonne of ammonia [29,30].

The main challenges for the basic materials industry to achieve carbon neutrality are providing high-temperature heat without carbon emissions and mitigating process emissions. Several factors complicate the transition required to achieve decarbonisation of these industries [31]. For example, long-lived assets slow down the potential pace of technology change. Industrial production units are characterized by high capital intensity [32] with a pay-back period of 20-50 years [33,34]. Anderson and Tushman [35] have analysed the historic development of cement and glass industries. They found that after an innovation has achieved economic viability, becoming the dominant process can take 5-20 years. The basic materials industry has high barriers to entry due to its high market concentration and strong buyer-supplier ties [36]. Basic materials are sold on a highly competitive and global market, further complicating a transition to carbon neutrality.

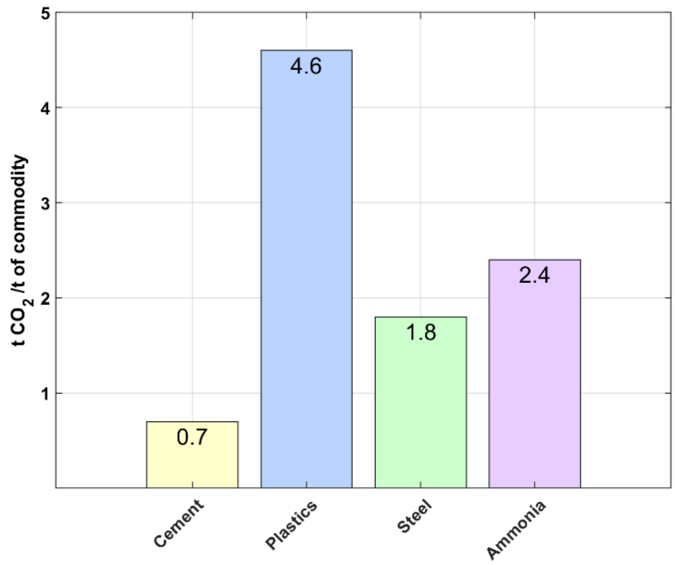


Figure 2.1: CO_2 intensity of production of steel, cement, plastics, and ammonia.

2.2 Key carbon dioxide abatement options for the industry

Table 2.1 gives details on options for reducing carbon emissions from the production of basic materials, the technological readiness and abatement potential. The technology readiness level (TRL 1–9) concept is used to assess and compare the maturity of technologies [37]. The technology journey begins from the point at which the basic principles are defined (TRL 1), on the path to full commercial operation in the relevant environment (TRL 9) [38].

Reduced use of materials, increased materials efficiency, increased circularity, and energy efficiency measures are important options for abating carbon emissions from basic materials production and reducing the need for primary production [39]. Yet these measures typically mainly contribute incremental reductions in material use and emissions. Under the objective of zero emissions production, these options therefore need to be accompanied by the implementation of more transformative measures and technologies, such as direct and indirect electrification, fuel shifting from fossil fuels to biomass/biofuels, and carbon capture and storage (CCS), which offer high CO_2 emission reduction potentials [32]. Several of these measures are not expected to be ready for market before 2030, although in some cases fuel shifting can be implemented in the short term, depending on the biomass feedstock and process. Replacing and retrofitting the existing industrial units also depends on the remaining lifetime of currently installed equipment, its operational costs, and expected costs for new technologies. Lead times for changing the main processes of the entire production system are often at least 20 years [40]. Suppliers (raw materials and process equipment) will also need to be developed and adapted, along with complementary industries (e.g., building materials manufacturers and component manufacturers), and consumers (increases in commodities prices), in parallel with technological development [41]

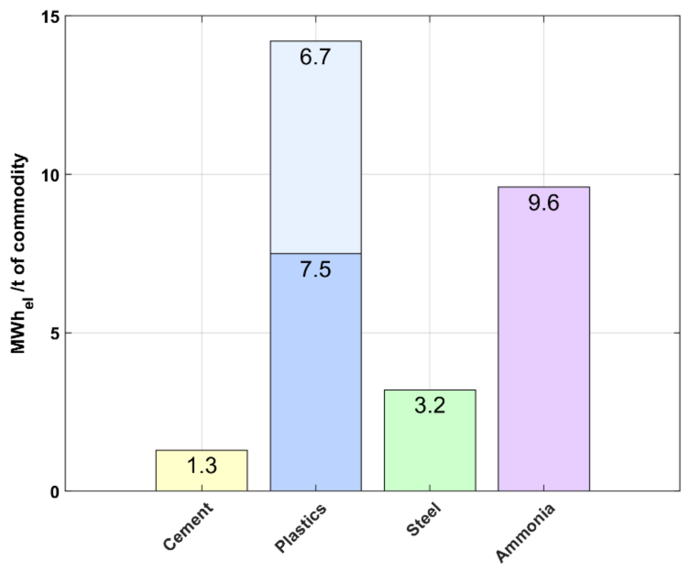
Table 2.1: Overview of the CO_2 emission reduction options for the basic materials industries including their abatement potential in % and TRL (technology readiness level).

Options for CO_2 emission reductions	Abatement potential	TRL	Reference
Steel industry			
Top gas recycling blast furnace/ basic oxygen furnace	5–10% 15%	7	[42–44] [45]
Steel reuse and recycling	17%	9	[46]
CO_2 capture technology [1]	50–75%	6–9	[47–49]
Biomass [2]	7–15% 23% 20–42% 31–57%	6–8	[50] [51] [52,53] [54]
Syngas (H_2 and CO) direct reduction (DR)	90%	9	[39]
Hydrogen direct reduction (H-DR)	100% [3]	5–7	[55–58]
Electrowinning	100% [3]	3–5	[59]
Cement industry			
Building design to minimise concrete	24% 33% 20–40%	9	[60] [61] [62]
Reuse of concrete elements	10–20%	9	[62]
Alternative fuels [4]	10–15%	9	[63,64]
Clinker substitution blast furnace slag, coal, waste fly ash calcined clays and limestone	 60–65% 40%	 9 7	 [65] [66]
CO_2 capture technology amine scrubbing calcium looping partial oxy-fuel/ full oxy-fuel direct capture	 90 % 90% 65–100% 64%	 6 6–8 4–6 4–5	 [67,68] [69,70] [70,71] [70,72]
Electrification + CO_2 capture technology	100% [3]	3	[73,74]
Plastics industry			
Material efficiency	14–35%	9	[28,75]
Energy efficiency and fuel change	15–40%	9	[76]
Recycling	22% 91–100%	9 5–6	[77] [39]
CO_2 capture technology [5]	55–90%	5–8	[28,77]
Biomass feedstock	100%	3–6	[78]
Electrification	100% [3]	3–4	[79]
Ammonia industry			
Steam methane reforming with CCS	80%	6–7	[77,80]
Biomass-to-NH_3	50%	5	[81–83]
H_2 from electrolysis [6]	100% [3]	7–9	[84,85]

[1] Post combustion capture of blast furnace emissions
[2] Substitute for pulverized coal injected (PCI) as a fuel in the blast furnace
[3] The CO_2 emission reduction potential depends on the composition of the electricity system
[4] Biomass as fuel in cement plants
[5] Capture CO_2 emission from the cracking process
[6] Alkaline electrolysis

2.3 Electrification of industry

The cost declines and low-carbon environmental impacts of wind and solar power as well as the possibility to harness low-cost electricity for flexible consumers have made direct and indirect (through hydrogen) electrification a key pathway towards electrification of the basic materials industry. Figure 2.2 gives electricity intensity in terms of MWh electricity per tonne of basic material, when production is electrified (cement [73], plastics [79], steel [86], ammonia [87]).



*Electricity demand for plastics production depends on CO_2 utilisation: the CO_2 emissions that arise from the process can either be captured and converted to olefins through a synthesis process, or they can be captured and stored. If all the CO_2 emissions that arise from the process are captured and converted to olefins through a synthesis process, the electricity consumption of the plastics production process is 14.2 MWh per tonne of plastics. If all the CO_2 emissions that arise from the process instead are captured and stored, the corresponding figure is 7.5 MWh.

Figure 2.2: Electricity intensity in MWh_{el}/t of commodity of the electrified basic materials industry.

Direct electrification refers to the direct use of electricity as an input (plasma rotary kiln, EAF, electrified heat of steam cracker) whereas indirect electrification refers to the production of hydrogen and hydrogen-rich fuels and feedstocks from electrolysis [88]. Using electrolysis to split water into hydrogen and oxygen seems to be the main option for indirect electrification presently considered by industry, although blue hydrogen—hydrogen from natural gas where the carbon released is stored underground—could possibly be used as well. Among electrolysis technologies, we consider alkaline because of its technological maturity and because it shows the lowest cost compared to other technologies [89]. The electrolyser has a high operational flexibility, i.e., this unit has a low minimum load (5-100%), short start-time (cold start to nominal load takes less than 20 minutes), and high ramp rate (hot idle ramp time takes 30 seconds) [90,91].

Steel industry. Figure 2.3 shows a schematic of the electrified steel production process assumed here: the hydrogen-based direct reduction process. It consists of hydrogen production in an electrolyser, HBI production in a DR shaft furnace, and steel production in an EAF. Hydrogen and HBI can be stored. During the iron production step, the iron ore pellets are reduced to direct reduced iron (DRI) by adding hydrogen as the reducing agent in a shaft furnace. To avoid re-oxidisation, the DRI is compacted into HBI, thereby enabling the DRI to be stored and transported without the need for special precautions [92]. In the steel production step, HBI is further converted to liquid steel in an EAF. The EAF is flexible in terms of changing the power consumption rate [93] and it can be stopped and started in response to the prevailing level of demand [94]. The direct reduction shaft furnace can be operated in a flexible manner between the minimum load level and rated capacity [95].

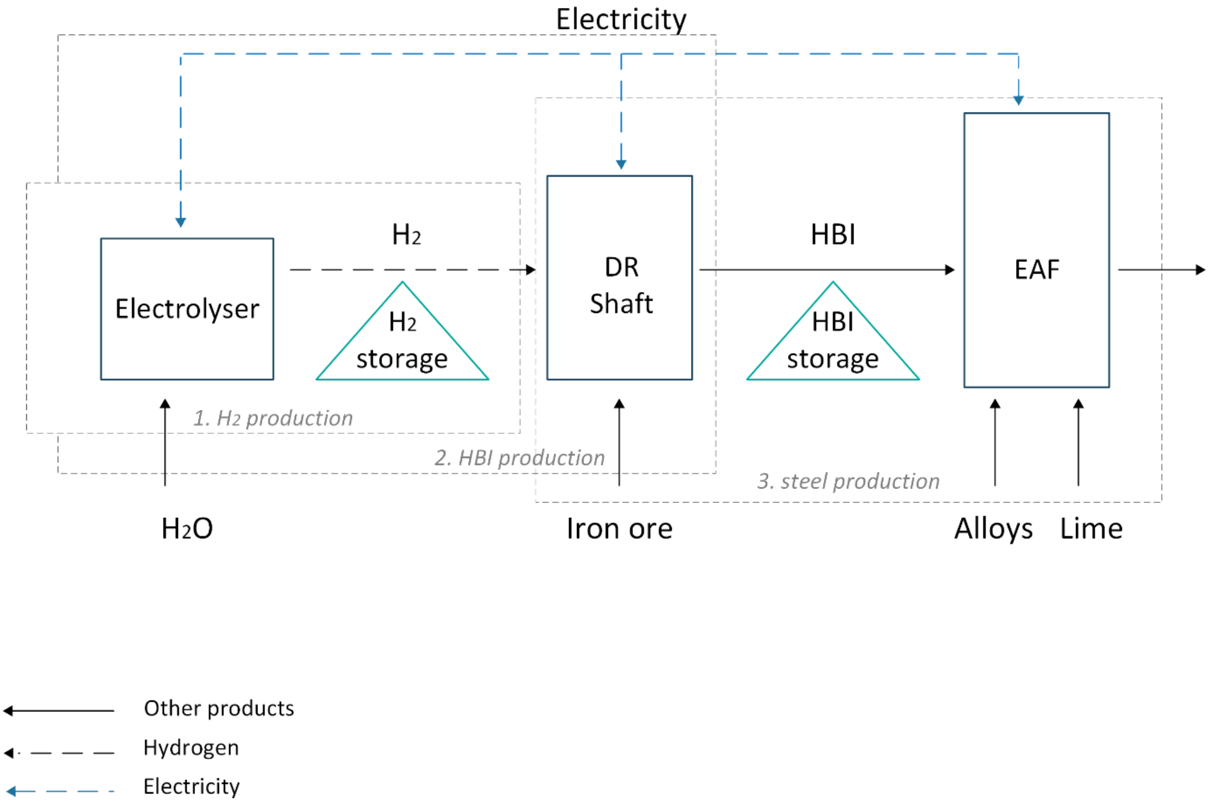


Figure 2.3: Schematic representation of the electrified steel production process.

Plastics industry. Figure 2.4 presents a schematic of the process for the electrified plastics production — via thermochemical plastic recycling [79] and waste gasification [96,97]. Table 2.2 gives an overview of the processes applied to produce plastics considered here, in terms of feedstock, process type and technology. A mix of waste and plastic waste is used as feedstock to produce plastic. The collected packaging plastic waste (household and industrial end use) is used as the plastics waste in this study. We assume that waste that is currently being incinerated is available for waste gasification to produce plastics; this is in line with the circular economy action plan adopted in Year 2020 (EU, 2020). In Sweden, around 80% of plastic waste is incinerated, while less than 10 % of the plastic flows are recycled for materials (PET bottles, electronic waste and sorted packaging) [98].

Table 2.2: Overview of processes configurations for plastics production.

	Route 1	**Route 2**
Feedstock	Plastic waste	Waste
Process	Thermochemical recycling	Gasification
Technology	Steam cracker (Fluidized bed reactor)	Steam cracker (Fluidized bed reactor)

The production of plastics can be divided into three main steps: olefins, plastic, and hydrogen production. Olefins are the building blocks for plastics production. The thermal cracking of the plastic waste ensures that a significant share of the plastic waste is directly recovered as olefins. In addition to olefins, thermochemical recycling of plastic waste and waste gasification produce a raw syngas, which is further reformed into pure CO and H_2. The reformed syngas as well as the CO_2 emissions that arise from the process can be used for methanol synthesis. The produced raw methanol is converted to olefins via the methanol-to-olefins process. Alternatively, the CO_2 can be captured and stored. The total electricity consumption of the plastics production process is in the range of 7.5-14.2 MWh per tonne plastics depending on CO_2 utilisation. In this work, we assume that the heat for the cracker is provided by electric heating, which is delivered through electrical coils installed in the bed material loop as explained by [99].

The steam cracker, steam reformer, and the synthesis and methanol-to-olefins processes have limited flexibility, i.e., they have to operate continuously without stops. For the steam cracker, the steam reformer and the methanol-to-olefins process, the output can fluctuate within the operational range of 100%–50% of full capacity. The operation of the synthesis process can be reduced to 25% of full capacity [100]. The temporal profile of the electricity consumption of the process can be made flexible through the storage of hydrogen and methanol. Methanol can be stored and exported for use as a base chemical at external production sites. The locations and capacities of the existing chemical factories are used in this work, while the capacity and location of other parts of the plastics recycling process are decision variables in the model.

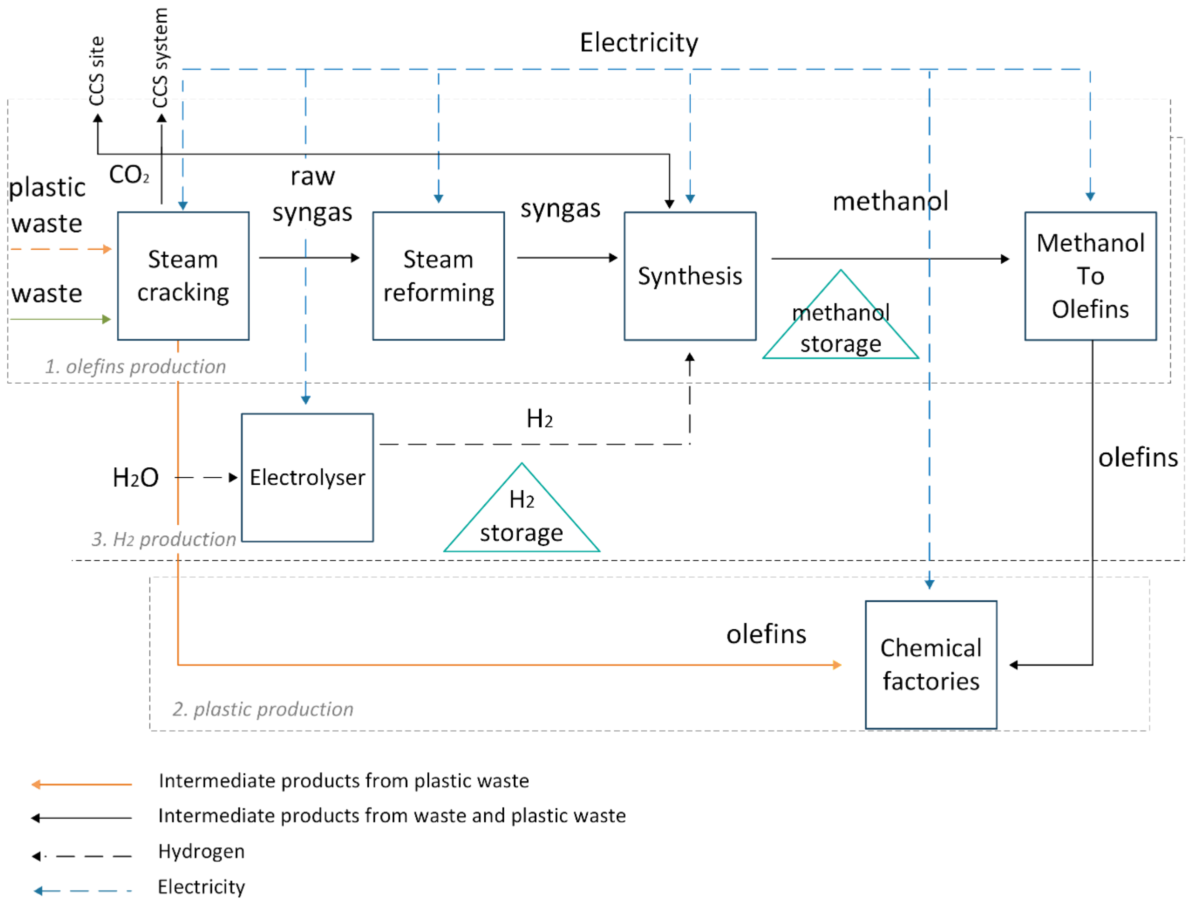


Figure 2.4: Schematic representation of the electrified plastics production process.

Ammonia industry. The electrified ammonia production process incorporates electrolysis for hydrogen production, an air separation unit (ASU) for nitrogen production, and the ammonia synthesis via the Haber-Bosch (HB) process (Figure 2.5). An ASU uses a cryogenic distillation process to separate ambient air into nitrogen and oxygen. All products can be stored in storage tanks [101]. The inlet air compressor is the main electricity consumer of an ASU [102]. The HB process combines elemental hydrogen and nitrogen under high pressure and temperature. The minimum load could be 20% [103] or 30% of total installed capacity [89]. Ammonia is transportable and storable [104].

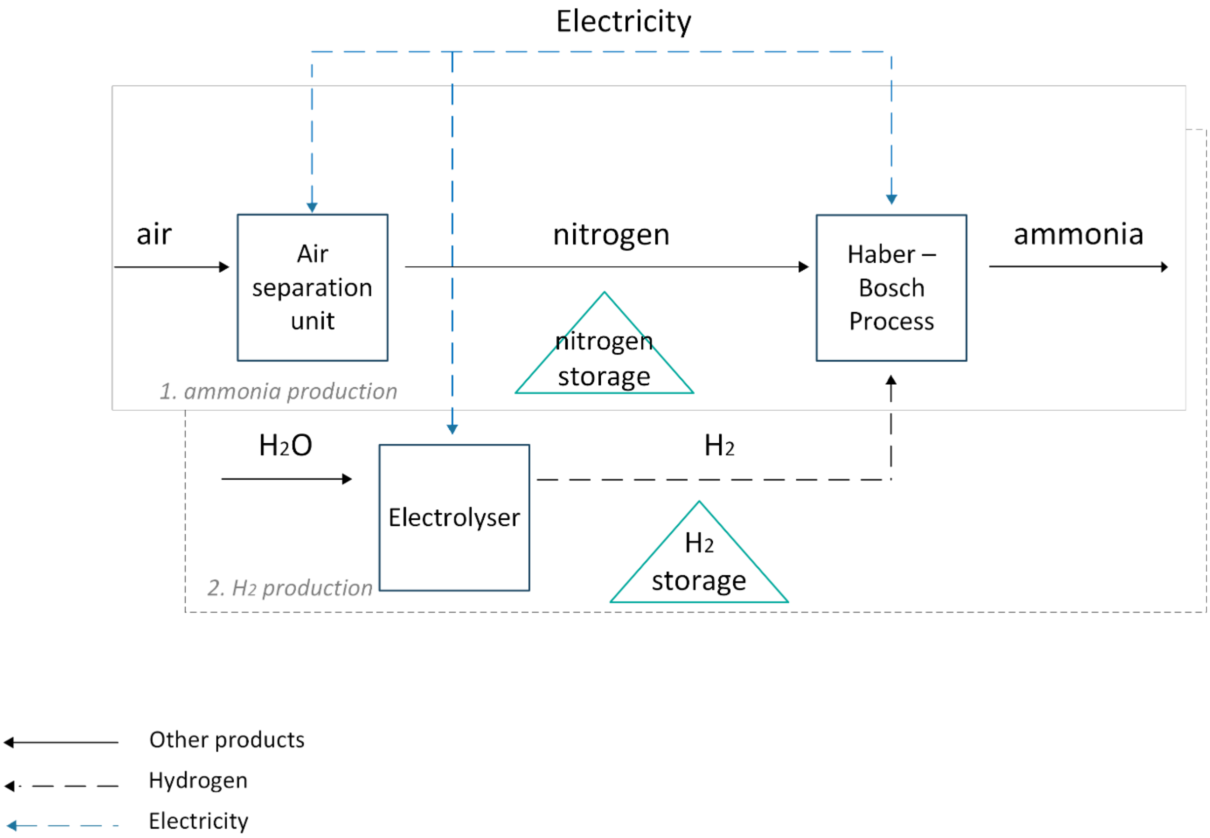


Figure 2.5: Schematic representation of the electrified ammonia production process.

Cement industry. In this work it is assumed that cement is produced using the electric plasma kiln explained by [73]. Even with electrification, the process-related CO_2 emissions from the cement production process remain, and the resulting CO_2 stream is pure, thus there is no need for CO_2 separation from the flue gas when applying CCS. Electrified cement production that uses plasma heating requires around 1.3 MWh of electricity per tonne of clinker (Figure 2.6). The electrified cement kiln is able to vary the output within the operational range down to 50% of full capacity. Note that the plasma kiln is not a near-term solution (TRL 3, see Table 2.1) since the electrification process needs to be developed, upscaled and optimised [105]. Yet, full scale implementation is expected by Year 2035 and investment costs are estimated at 50 €/ton of cement [73].

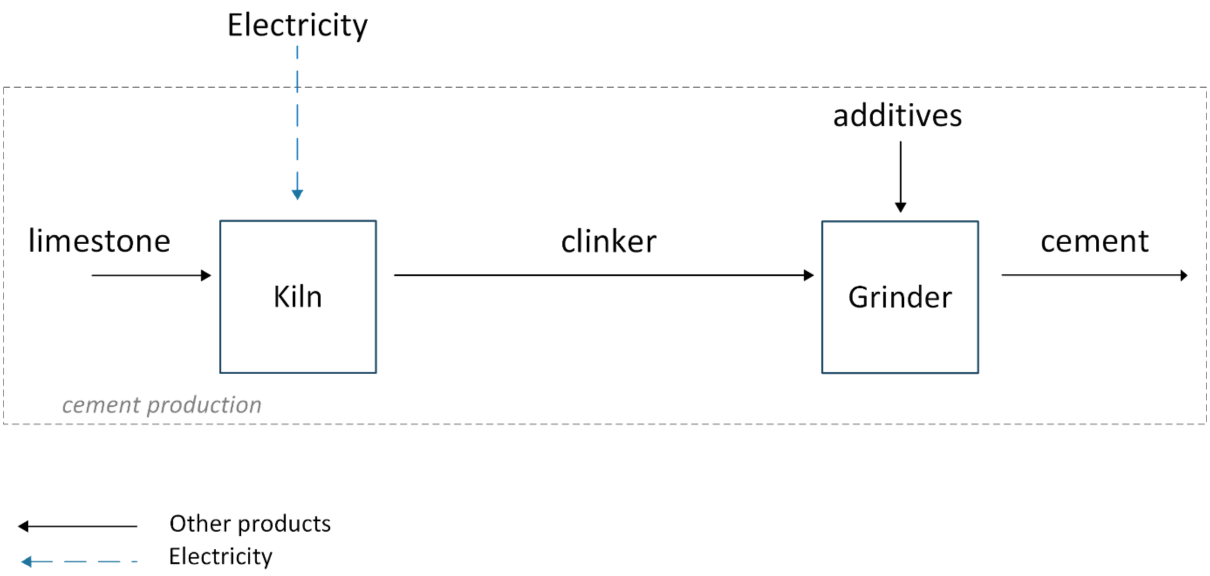


Figure 2.6: Schematic representation of the electrified cement production process.

2.4 Industrial flexibility

Three types of flexibility for the electrified industry were considered in this work: flexibility in relation to time, location and CO_2 utilisation (Table 2.3). This section describes the definitions and approach which was proposed to present flexibility options in the energy systems model.

Flexibility in time. Flexibility in time is defined by operational flexibility, i.e., the ability of the industrial unit to vary the output within the load ranges. In the absence of flexibility in time, the capacity utilisation rate is 100%, i.e., there is no investment in overcapacity and storage. With flexibility in time, storage of commodities (e.g., hydrogen, hot-briquetted iron, nitrogen, and methanol) allows for rescheduling electricity consumption to periods with lower cost when available.

By applying a mixed-integer linear optimisation model, Roh et al.[106] have analysed impacts of different German electricity price profiles on the sizing and operation of the chlor-alkali electrolyser employing a bifunctional cathode. They conclude that flexible operation of the chlor-alkali electrolysis leads to savings in operating costs but to increased capital investment due to retrofitting for overcapacity and is only economically viable for future forecasted electricity price profiles (which are more variable than the 2017 profile.

Flexibility in location of new industrial facilities. The electrification of the basic materials industry has the potential to change the cost structures of industrial production, thereby impacting the most cost-effective geographical locations for commodities production. In the urgency of abatement of industrial emissions, the optimal location for production may shift from being close to demand and/or raw material supply centres to places where zero-emissions electricity is readily available at low cost, or where there are favourable conditions for CCS [21].

Flexibility in location is defined by the ability to export commodities. With flexibility in location, it is possible to locate new industrial units into regions without existing basic materials industries, increase capacity and/or production in the regions with existing industry, and separate parts of the existing supply chain. Distance-dependent transport costs for commodities are assumed, i.e., we consider the transport distance between regions and the amount of transported commodity. To represent some of the material and immaterial values in the current industrial sites, i.e., regions with existing industries, we apply an investment penalty for investments in new production sites for regions without existing industries: a 50% increase in investment cost—compared to investments in existing sites—for units producing commodities in regions without existing production of that basic material.

Erickson et al. [107] have analysed the influence of the electricity emission factor, natural gas (NG) availability, biomass availability and iron ore reserves on the location of steel production. They show that strategically positioning steel production (70 million tonnes of steel produced via BF-BOF and 4 million tonnes of steel produced via NG-DRI-EAF) in regions with access to biomass and renewable electricity could reduce the current GHG emissions of the steel industry by about 5%, which is far from what is needed to achieve the climate goals. This thesis attempts to identify the factors that influence the allocation of new electrified processes.

Flexibility in CO_2 utilisation. For some basic materials, such as plastics, electrification is not enough to eliminate production CO_2 emissions. Here, we assume that for plastics the process-related CO_2 can be captured and converted to olefins through a synthesis process (CCU mode) and/or captured and stored (CCS mode). The term flexibility in CO_2 utilisation refers to the ability of production units to vary between CCU and CCS.

Ahlström et al. [108] have studied the role of the biomass gasification process with flexibility in CO_2 utilisation in the electricity system by means of a linear cost-minimisation model. They conclude that the usage of CO_2 for net-negative emissions gives lower costs than enhanced biofuel (electro-fuel) production and that the amount of CO_2 utilised for biofuel production depends on the availability of low-cost electricity.

Table 2.3: Definition and description of the industrial flexibility options defined in this work.

	Flexibility options of industry		
	Flexibility in time	*Flexibility in location*	*Flexibility in CO_2 utilisation*
Definition	The ability of the industrial unit to vary load	The ability to move/separate parts of the electrified industry supply chain	The ability to capture CO_2 and use for plastics production and/or store with CCS
How to account for flexibility options: model parameters	Load range, start-up cost, start-up time	Ability to trade commodity, cost of trading commodity, distance, cost of new sites	Cost of storing CO_2, availability of raw material, cost of raw material
Variables representing impacts of flexibility options	Capacity of production units and commodities storage	Commodities trade flows	Production of industrial units
Implications	Increase in investment cost and decrease in operational costs (i.e., electricity cost)	Increase in transportation cost and decrease in operational costs (i.e., electricity cost)	Depend on other flexibility options - increase/decrease in feedstock cost and increase/decrease in operational costs (i.e., electricity cost)

2.5 Supply of electricity for industrial electrification

Direct and indirect (through hydrogen) electrification of industry will result in a steep increase in electricity demand. Investment costs for wind and solar generation technologies have decreased faster than initially projected, which will facilitate investments in new electricity production. During the last decade, the global weighted-average total installed costs of solar PV, onshore, and offshore wind fell by 85%, 31%, and 32%, respectively [18]

In the EU, the proportion of renewable energy in final energy use has increased from 9.6% in 2004 to 22% in 2020 [109] resulting in a decline in the carbon intensity of electricity generation from 399 gCO_2/kWh in 2004 to 215 gCO_2/kWh in 2020 [110].

Due to low environmental impacts of electricity generation technologies based on renewable energy sources (wind and solar power) together with the above-mentioned cost reduction (which has resulted in improved cost-competitiveness relative to both fossil-fuel and nuclear power), wind and solar power are expected to supply a large share of the future demand for electricity. The value of variable renewable energy (VRE) to the electricity system is reduced as its share in the electricity system increases due precisely to its variability [111]. Storage (e.g., stationary batteries, hydropower reservoirs, or hydrogen storage) but also the linkage of the electricity system to other sectors such as the heat, transport, and industry sectors can mitigate the decline in the value of VRE to ensure cost competitiveness despite high shares of VRE in the electricity system [112,113]. As mentioned above, the reduced cost of wind and solar makes it likely that the expansion in electricity over the next decade will mainly be in wind and solar, which implies that industries—and in particular EIIs—need to consider an increase in volatility in electricity prices, although the average price may not be higher than at present (before Russia's invasion of Ukraine, but provided that this war ends).

Figure 2.7 presents the average electricity price, together with a volatility index for the profiles representing electricity prices of Year 2018 in Germany and the UK (obtained from Epexspot [114] and NordPool [115], respectively), and the electricity price profiles for Year 2050, derived from the electricity system investment model H2D [116]. The H2D model has a 3-hour time resolution and a geographic resolution based on the major bottlenecks in the transmission grid. Northern Europe is subdivided into 12 regions, and the current configuration (Year 2018) of the bidding zones is modified. Therefore, the Year 2050 electricity prices deployed in this work do not correspond to those of the entire countries, but instead to the regions representing southern Germany and Scotland. These regions are selected to reflect different conditions for variable renewables. The price profiles for Year 2050 are converted to an hourly resolution through linear interpolation within each 3-hour time segment.

The volatility index, I_v, of the electricity price profile is defined as:

$$I_v = \frac{\int_{t_1}^{t_2} (p_t - p^{average})^2 dt}{100(t_2 - t_1)} \qquad (1),$$

where p_t is the electricity price at time t, and $p^{average}$ is the average electricity price. The volatility index is introduced and calculated according to the method applied by Beiron [117]. The electricity price p_t corresponds in this work is close to the wholesale price of electricity. Note that the modelling in this work solves for the lowest electricity cost and, thus, does not include any profit margins or market imperfections (but perfect foresight). In reality, EIIs in the EU typically purchase a large share of their electricity through power purchase agreements

(PPAs) in order to secure a predictable electricity price (lower than what would have been obtained from the spot market price available at market prices such as the Noord pool market). However, the modelling solves for what is a reasonable societal cost of electricity.

The volatility index indicates an increase in the number and duration of both the high- and low-price electricity periods due to high shares of renewables in the two countries in Year 2050, as compared with the Year 2018 electricity price profiles. For the electricity system in the northern UK, the extensive low-electricity price periods in Year 2050 result in an average electricity price that is 20% lower than the Year 2018 UK prices as well as lower than that of southern Germany during the same period.

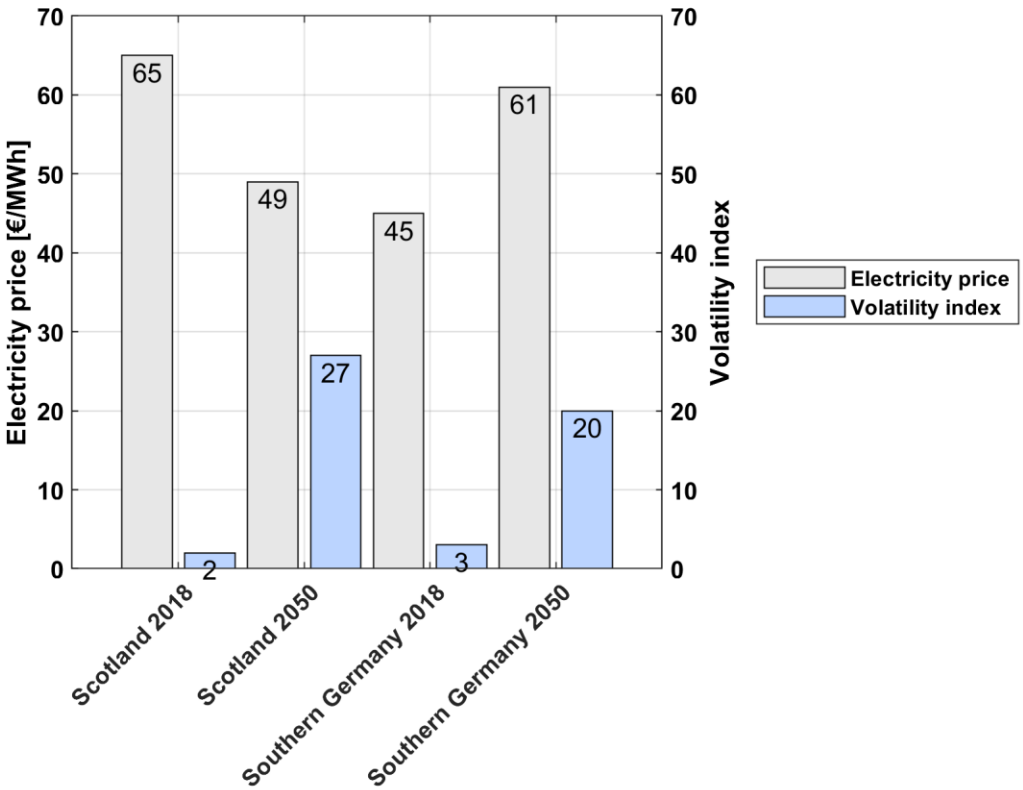
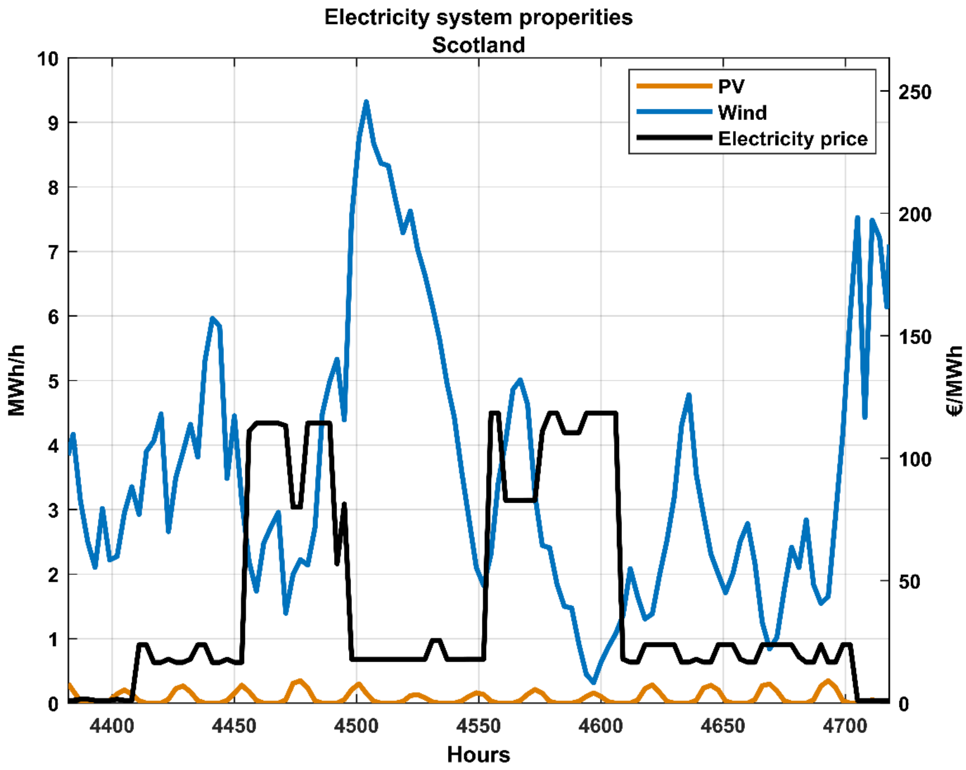
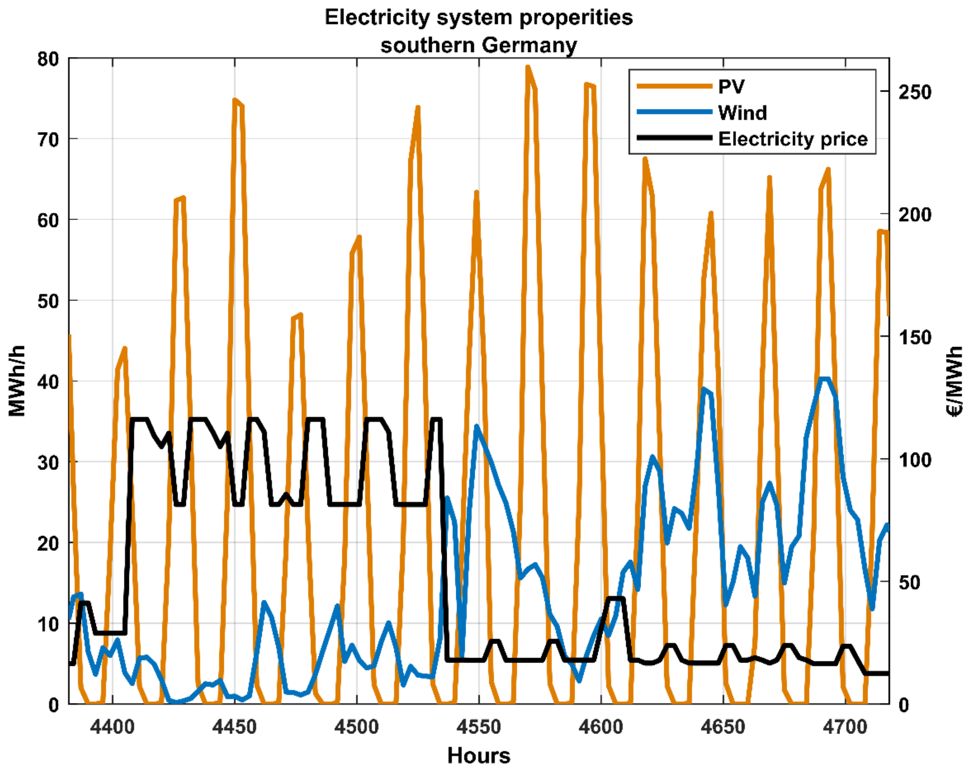


Figure 2.7: Average electricity prices and electricity price volatility indices for Germany and the UK in Year 2018, and for southern Germany and Scotland in Year 2050.

Solar and wind power impacts the electricity price volatility in different ways [118]. Figure 2.8 shows the wind and solar power generation levels together with the electricity prices for southern Germany and Scotland for 3 weeks in July 2050, as obtained from the modelling. The wind power variations are irregular, the production profile shows variations on a timescale of a few hours to a few days. The solar variations are diurnal due to their day-time and night-time dependency.



a)



b)

Figure 2.8: Electricity price profiles and the levels of wind and solar power generation for: (a) Scotland; (b) southern Germany, for three weeks in July 2050.

2.6 Implication of the industry electrification

As shown in Table 2.4, several studies have been published in recent years on the topic of electrification of industry, with the aim of determining the impacts of electrified industry on the electricity system (e.g., [116,119–124]). The extent to which electrification will be implemented in the industry is uncertain.

Lechtenböhmer et al. have investigated annual industrial electricity demand of the energy-intensive basic materials industries (steel, cement, glass, lime, petrochemicals, chlorine, and ammonia) in the EU by the means of "what-if" explorative analysis. With the assumption that the demand for basic materials is maintained at current levels, they find the resulting electricity demand to be 1,500 TWh. This would mean a more than 50% increase in the present total EU electricity demand, which currently amounts to about 2,800 TWh (2019) [119]. Neuwirth et al. have assessed the electricity demand for hydrogen in north-western Europe by the means of a bottom-up approach. They assume that hydrogen is used as feedstock in the steel industry and as fuel for high-temperature process heat for the production of non-metallic minerals, basic chemicals, non-ferrous metals and paper, resulting in an annual hydrogen demand of about 260 TWh [120].

The above works [119,120] indicate that new electricity demand from industry will require large investments in electricity generation capacity. Thus, it will be a challenge to meet the electricity demand for electrifying the industry, in particular since a cost-efficient electrification will require flexibility in the electricity system. It is therefore important to understand the possibilities and requirements for flexibility, and how the future electricity system can interact with an electrified basic materials industry, motivating the present work.

Walter et al. have shown the impacts of the hydrogen demand (varying it from 0 TWh_{H2} to 2,500 TWh_{H2} in steps of 500 TWh_{H2}) on the future European zero-emission electricity system, taking into consideration flexibility in time (hydrogen storage and investments in overcapacity of hydrogen-consuming industries) and location. The upper hydrogen demand level (2500 TWh) is set according to the European hydrogen pathway [125]. They find that the scenarios implementing flexibility options (flexibility in time (by means of both overcapacity and storage), and in location) for the electrolyser have the lowest production costs [126].

Applying a semi-heuristic, cost-minimising investment model, Göransson et al. [116] have investigated the impacts of electrification of the industrial, transport, and heat sectors on the north European electricity system. They demonstrate that sector coupling together with flexible electricity consumption for various sectors would reduce overall system costs, as compared to electrification without flexibility provision. Moreover, flexible consumption of electricity for hydrogen production reduces the need for peak generation compared to an inflexible consumption of electricity, thereby reducing the number of hours with very high electricity prices as well as the annual average electricity price.

By implementing a techno-economic optimisation model of the European electricity system, Öberg et al. [122] have shown that flexible operation of the electrolyser, i.e., the ability to follow electricity price variation due to overcapacity of the electrolyser and hydrogen storage capacities, have significant impacts on the cost of hydrogen. Unlike Walter et al., Öberg et al. considered hydrogen demand connected to its usage, i.e., they consider additional hydrogen demand from transport and industries (ammonia, cement, and plastics). They conclude that the characteristics of the hydrogen demand also impact hydrogen production costs. Flexible operation of industry (i.e., overcapacity is available) can reduce the cost of hydrogen production by up to 35% compared to constant operation of the industrial units. However, the model developed by Öberg et al. does not account for the additional cost for overcapacity of industrial units and storage of the products or intermediate products.

Neumann et al. [123] have analysed the impacts of the hydrogen pipelines network in net-zero CO_2 scenarios for European electricity system. They used a linear programming optimisation model with high level of spatial, temporal, technological and sectoral resolution. The model results show that a hydrogen pipelines network reduces system costs, with highest cost benefits when electricity grid expansion cannot be realised as compared to scenario without hydrogen and electricity grids expansion. They also show that flexibility in time of the electrolyser promotes renewables integration to satisfy addition electricity demand.

Applying a linear optimisation model of Kazakhstan's electricity system, Bogdanov et al. [124] investigated the transition toward zero carbon emissions in electricity, heat, transport and industry sectors. The industries which were considered in the study are cement, iron and steel, chemicals, aluminium, pulp and paper and desalination. The impacts of electrification only on the production costs of chemicals and desalination are traced, i.e., the model optimise the capacity and operation of the methanol and ammonia production units. For cement, steel, aluminium, pulp and paper industry the model only optimises the operation, raw materials and energy consumption profiles, i.e., investments in industrial capacities for these industries are not included. The model results show that large-scale electrification of the heat, transport and industry sectors that have flexibility in relation to time leads to a total system cost decrease as compared to scenarios without flexibility in time.

Lechtenböhmer et al. and Neuwirth et al. have estimated the annual industrial electricity demand when electrifying basic materials industries but does not consider how the electrified industry will influence future investments in electricity generation in different regions remains in these studies. Studies from Göransson et al. and Neumann et al. have demonstrated the impacts of large-scale electrification on the electricity system composition including investments in electricity generation capacity. They studied the implication of flexible hydrogen production, i.e., investments in overcapacity of the electrolyser and hydrogen storage, on the total system cost. The studies from [122,126] have also shown that flexibility in the time of the electrolyser can have a major influence on the hydrogen production cost. The impacts of industrial electrification on process design (investments in industrial overcapacity and available commodities storage options) are not studied in the previous works. Bogdanov et al. have captured the impacts of the large-scale electrification of the industry on the operation of the industrial units as well as the chemicals production cost, i.e., investments and operating costs of industrial units are considered. However, the location of future industrial plants (including commodities trade) was not analysed in the above works.

The present work is further contributing to the field by studying the impacts of industrial electrification on process design (investments in overcapacity for industrial units and available storage options for commodities) and future industrial plants' location (including commodities trade). In addition, the work illustrates the impact of industrial electrification on the electricity system and how industrial flexibility options impact the electricity system composition and the electricity price.

Table 2.4: Overview of previous studies that investigate electrification of the industry sector.

Reference	Model	Geographical scope	Time resolution	Aim	Subsectors	Industrial flexibility options	Main conclusions
Lechtenböhmer et al.[119]	“What-if” explorative analysis	EU	One year	The impacts of electrification of the basic materials industries on the electricity system	Steel, cement, glass, lime, petrochemicals, chlorine, and ammonia industries	No flexibility options	The electrification of the production of basic materials is technically feasible, yet, can have major implications on the interaction between the industries and the electric systems
Neuwirth et al. [120]	Plant-specific assessment approach	North-Western Europe	The period from 2025 to 2035 with 5-year time steps.	The potential hydrogen demand from industry and its geographical distribution	Steel, non-metallic minerals, basic chemicals, non-ferrous metals, paper and printing	No flexibility options	The results provide a detailed view of the potential hydrogen demand in the EU and its geographical distribution until 2035.
Göransson et al. [116]	A semi-heuristic, cost-minimising investment model	EU – 12 regions	2-week segments with a 3-hour time resolution	The impacts of electrification of the steel industry, passenger vehicles, and residential heat supply on the electricity system	Electricity system, steel industry, passenger vehicles, and residential heat supply	Flexibility in time of electrolyser	The flexible demand for electricity in different sectors would reduce overall system costs, as compared to electrification without flexibility provision.
Walter et al. [126]	A linear optimisation model. Objective: minimise running and investment costs	EU – 22 regions	730 consecutive time-steps of one year	The influence of the hydrogen demand on the electricity system	Electricity system, hydrogen demand, electrification of passenger car fleet and the heavy-duty vehicle fleet, electricity demand from replacing natural gas-based heating with decentralized heat pumps.	Flexibility in time and in location of electrolyser	The strategic localisation of hydrogen production, a strong acceptance of wind and solar power expansion or a low total hydrogen demand, and flexible industries will enable low-cost hydrogen production.
Öberg et al. [122]	A linear optimisation model. Objective: minimise running and investment costs	EU – 4 regions	365 time-steps per one year	The analysis of the time-resolved cost of hydrogen in a future electricity system	Electricity system, electrification of cars, light trucks, heavy trucks, and buses, steel, ammonia, and cement industries	Flexibility in time of electrolyser and industrial units	Flexibility in hydrogen-based industries reduces the cost of hydrogen, as compared to a constant hydrogen demand.
Neumann et al. [123]	A linear optimisation model. Objective: minimise operation and investment costs	EU – 181 regions	Three-hour resolution of a year	The impacts of electricity transmission lines on the electricity system	Electricity, buildings, transport, agriculture, and industry (ammonia, chemicals and steel) sectors	Flexibility in time of electrolyser	A hydrogen pipelines network reduces system costs, with highest benefits when electricity grid expansion cannot be realised. The hydrogen networks can only partially substitute for power grid expansion, and that both can achieve strongest cost savings
Bogdanov et al. [124]	A linear optimisation model. Objective: minimise operation and investment costs	Kazakh-stan	The period from 2015 to 2050 with 5-year time steps. Hourly resolution of each year.	The impacts of sector coupling on the electricity system.	Electricity, heat, transport, and industry (cement, steel, chemicals, aluminium, pulp and paper and desalination) sectors	Flexibility in time of electrolyser and industrial units	The electrification and integration of sectors enable additional flexibility, leading to more efficient systems and lower energy supply cost, even though the integration effect varies from sector to sector.
Toktarova et al. (this work and **Paper V**)	A linear optimisation model. Objective: minimise running and investment costs	EU – 22 regions	730 consecutive time-steps of one year	Mutual impacts of electricity system and the electrified industries	Electricity system, electrification of passenger car and the heavy-duty vehicle fleets, electricity demand from replacing natural gas-based heating with decentralized heat pumps, and basic materials industries	Flexibility in time, location and CO_2 utilisation of industrial units	For the electrified industries with high operational flexibility and dependency on hydrogen, the availability of low-cost electricity is the main parameter that affects the spatial distribution of new plants.

3 Methodology

This section provides an overview of the models and most important assumptions and input data used in the appended papers (Figure 3.1).

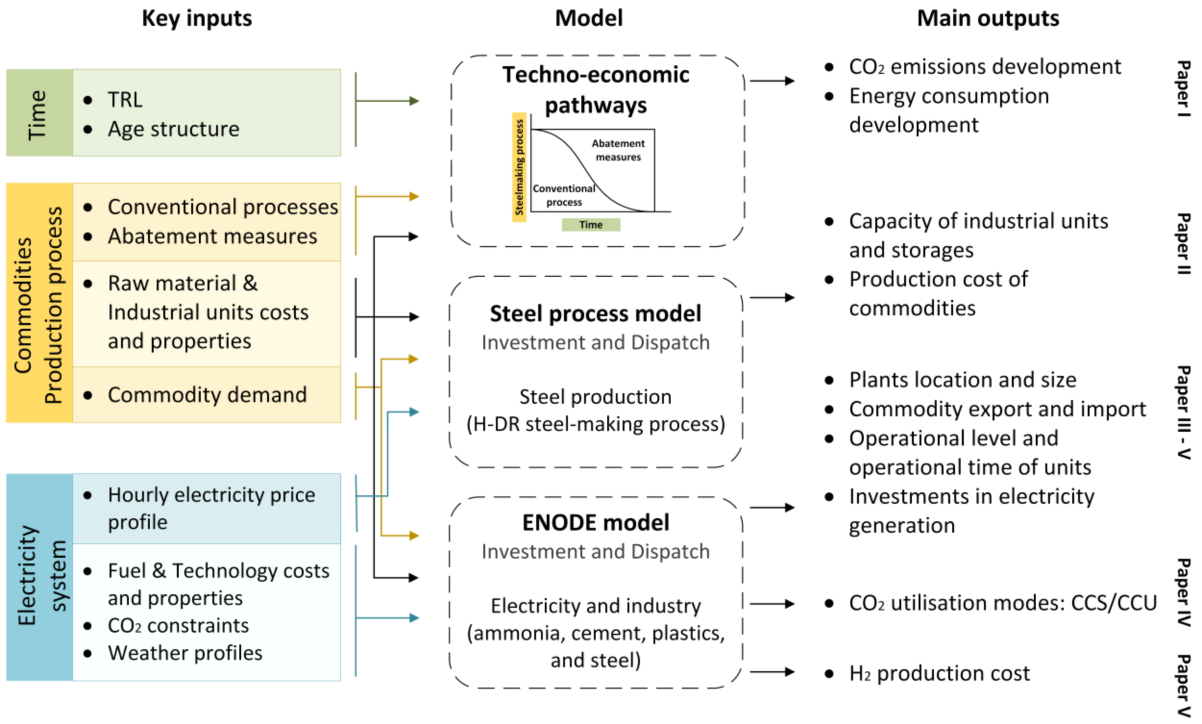


Figure 3.1: Overview of the models used in this work and their main inputs and outputs.

In **Paper I**, the concept of techno-economic pathways is used to investigate the potential implementation of CO_2 abatement measures over time towards a basic materials industry without carbon emissions for the case study of Swedish steel industry.

For **Paper II**, a Steel Process (SP) model is developed to investigate the impacts of electricity price variations on electrified steel production. The SP model allows analysing implications of the flexibility in the time of the industry based on the results for capacity of industrial units and storages (i.e., HBI and hydrogen).

Paper III introduces and analyses flexibility in location of the electrified steel production, in addition to flexibility in time (**Paper II**).

In **Paper IV**, the characteristics of an electrified plastic production process allow for studying the impacts of flexibility in CO_2 utilisation.

Paper V investigates the electrification of the ammonia, cement, steel, and plastics industries and the impacts thereof on the electricity system, as well as the mutual impacts of the respective industries' electrification. In addition to flexibility in location for new industries, i.e., trade of commodities, we studied flexibility in location of the electrolyser; we also included hydrogen trade via pipeline network.

In **Papers III-V**, we further develop an existing linear electricity system optimisation model, ENODE, and apply it to study the interactions between an electrified industry (Section 2.3) and the electricity system. The ENODE model minimises the cost of investments and operation to meet the electricity demand. Our further-developed version also provides the demand for commodities (i.e., ammonia, cement, plastics, and steel).

3.1 Overview of input data

As indicated by the arrows on the left-hand side of Figure 3.1, several of the models (i.e., the techno-economic pathways, the Steel Process (SP) model and ENODE) use the same or similar input data.

All papers (**Papers I-V**) apply economic data for investments and operational costs of the industrial units, as well as the raw material consumption levels and associated costs. The average technical lifetime of industrial units and technology readiness levels of CO_2 abatement measures are used to design a development timeline for the pathways in **Paper I**. The selection and combination of the CO_2 abatement measures in **Paper I** are made in line with governmental climate goals and the visions of the industry, as well as being based on a comprehensive literature review. Investment costs and fixed/variable operation and maintenance (O&M) costs for electricity generation technologies and hourly generation profiles for solar and wind power are considered in **Paper III-V**.

Assumptions on commodities demand are utilised as an input in **Papers II–V**. In **Paper II**, it is assumed there is demand for steel all year around, i.e., 8,760 hours per year, with the demand expressed as 1 tonne per hour. In **Papers III** and **V**, the current production of commodities is used as the regional demand for commodities to reflect the connection between the basic materials industry and the location of other industries. **Paper IV** uses the current (2020) demand for plastics. In **Papers III-V**, the annual demand for commodities is given exogenously while the hourly electricity demand from EIIs is endogenous, thus investments in industrial units as well as the operation of these units are a result of the optimisation.

Hourly electricity price profiles representing two regions with different conditions for renewable electricity (southern Germany and Scotland) are inputs in **Paper II**. In addition to the new electricity demand from industry, present demand is used in **Papers III-V**. The present electricity demand is based on annual electricity consumption levels in the European countries, obtained from Eurostat [127], and is subject to an hourly demand profile obtained from [128].

In **Paper V**, the electricity demand from transport and heat is added exogenously to the present electricity demand. The electricity demand from heat is the electricity required to replace individual natural gas-based heating with decentralised heat pumps in Germany and the UK [116]. The electricity demand from the transport sector is modelled based on [129]. This model considers full electrification of the passenger car fleet and partial (60 %) electrification of the heavy-duty vehicle fleet.

The outputs of the methods are detailed in Chapter 4.

3.2 Techno-economic pathways (Paper I)

The techno-economic pathways are defined as a series of technological and economic investments that connect current industry configurations to a desirable low-carbon future [130]. Through technological characteristics, the pathways reveal the sectoral-level changes required to meet climate targets. The pathway analysis in **Paper I** involves the following steps:

1. Definition of inputs for the techno-economic modelling in terms of costs, CO_2 reduction potential, and specific energy inputs of CO_2 abatement measures;

2. Verification that the selection and combination of CO_2 abatement measures are in line with governmental climate goals, as well as the literature;

3. Design of pathway time-line of pathways based on the pace of decommissioning the conventional steel production technologies, considering the assumed development of the technology readiness levels of the included CO_2 abatement measures; and

4. Based on the technology readiness level time-line, estimation of a time-line for investments in abatement measures to replace current processes, prompting a shift in innovative technology diffusion patterns.

The techno-economic pathways are applied to estimate the evolution of the levels of CO_2 emissions and energy consumption over time, as well as the cost of steel production.

3.3 Optimisation models

The energy systems models allow for the formalization of scattered knowledge regarding the interactions in the energy sector and the effects of system changes. The building blocks of a model can include economical, technical, environmental, and even social elements, but most models focus on the former two. Energy models can be classified in many ways; according to Pfenninger et al. there are four categories of models: energy systems optimisation models, energy systems simulation models, power systems and electricity market models, and qualitative and mixed-methods scenarios. The energy systems models provide a range of alternatives to represent energy systems according to different scenarios, which can help inform policy- and decision-makers in their planning processes and policy recommendations [131]. In this work, two linear cost-minimising modelling approaches with different system setups have been utilised: the Steel Process (SP) model and the electricity system optimisation model, ENODE.

3.3.1 Modelling resolution

Geographical scope. As mentioned in Chapter 1, the geographical coverage of this work ranges from single-node (Southern Germany and Scotland - **Paper II**) to multi-node approaches (Northern Europe - **Papers III–IV** and Europe - **Paper V**).

The spatial consideration of the single region, i.e., mode, does not allow consideration of the potential benefits of trading electricity and commodities with other regions. Thus, the need for self-sufficiency in the investigated region is over-estimated by applying this approach [132].

The regional division of the EU area, as used in **Papers III–V**, was developed through previous work [133,134] and was designed to describe major bottlenecks in the transmission grid. In **Paper V**, the area of the EU (excluding Cyprus and Malta), UK, Norway and Switzerland was sub-divided into the following 22 regions (see Appendix A, Figure A.1): Northern Sweden (SE_N); Southern Sweden (SE_S); Northern Germany (DE_N); Southern Germany (DE_S): Estonia, Latvia, and Lithuania (BAL); Northern Poland (PO_N); Southern Poland (PO_S); Ireland (IE_T); Norway (NO_T); Portugal and Western Spain (IB_W); Eastern Spain (IB_E); Northern France (FR_N); Southern France (FR_S); Switzerland and Northern Italy (ALP_W); Southern Italy (IT_S); Austria, Czech Republic, and Slovakia (ATCZSK); Croatia, Slovakia (Slovak Republic), and Hungary (CRSIHU); Romania, Bulgaria and Greece (ROBGGR); Belgium, Netherlands, and Luxembourg (BENELUX); Finland (FI_T); Scotland (UK_N); and Southern UK (UK_S). Within the investigated regions, it is assumed that electricity can be transmitted without internal congestion. Trade between regions is limited by the transmission capacity with the existing grid capacity as a starting point, and the possibility to invest in additional capacity. In the current model, investments in additional grid capacity are constrained by the projected capacity increases for Year 2040 provided by ENTSO-E [135].

Time resolution. As mentioned in Section 1.1 (See Table 1), three different time resolutions are applied in the appended papers: i) 1 hour (**Paper II**); and ii) 12 hours, where the time-steps are averages for the hours of 06–17 and 18–05, so as to represent a day and a night step, respectively (**Paper III**); and iii) 730 consecutive time-steps over a period of 1 year, where the length of the time-steps varies from 5 to 19 hours (**Papers IV** and **V**). A time-period clustering technique that retains the chronology throughout the year is applied with the heuristic Ward method described by Pineda and Morales [136].

The importance of temporal resolution when modelling electricity systems with a high share of renewables has been shown by Haydt et al . They analysed different models (integral with a load-curve of 9 time slices, semi-dynamic with 288 time periods, and a dynamic approach with hourly modelling) for balancing the electricity supply sources and the electricity demand. Haydt et al. [137] found that models that do not consider the variability of demand and supply variations may over-estimate the levels of electricity generation from renewables and, thereby under-estimate the needed installed capacity, as well as the levels of CO_2 emissions.

3.3.2 Steel process model (**Paper II**)

The Steel Process (SP) model was developed in this thesis to study the impacts of electricity price variations on steel production capacities that apply the hydrogen direct reduction (H-DR) process. Both actual and modelled electricity prices are deployed in the analysis. The electricity price profiles representing current (2018) electricity prices in Germany and the UK are obtained from Epexspot [114] and NordPool [115], respectively. The electricity price profiles for 2050 are derived from the electricity system investment model H2D [116].

The overall objective of the SP model, which is a linear optimisation model, is to design the operational times and operational levels of the steel production capacities, as well as the utilisation of storage units, such that the steel demand is satisfied at the lowest total steel production cost C^{tot}, i.e., the sum of the costs of investment C_p^{inv}, operation $C_{p,t}^{run}$, and cycling $C_{p,t}^{cycl}$. The total steel production cost, which should be minimised, can therefore be written as:

$$minC^{tot} = \sum_{p\in P} C_p^{inv} i_p + \sum_{p\in P}\sum_{t\in T}(C_{p,t}^{run} g_{p,t} + C_{p,t}^{cycl}) \tag{2}$$

where P is the set of steel production capacities (electrolyser, DR shaft furnace and EAF) and storage technologies (hydrogen and HBI storage units), and T is the set of time-steps.

3.3.3 ENODE (**Papers III-V**)

ENODE was designed by Göransson et al. [138] to investigate the interactions between VRE and thermal generation technologies. In the current thesis, we further develop ENODE and apply our enhanced version to study the interaction between the electrified industry and the electricity system. Our version minimises the cost for investments in and operation of the electricity system and electrified industry, while meeting the demands for electricity and commodities. The ENODE model is a green-field model, in which a new system is designed from scratch.

The objective function is expressed as:

$$\begin{aligned} min\colon C^{tot} = &\sum_{r\in R}\sum_{p\in P\setminus P^{transm}\cup P^{H_2\,pipes}} i_{p,r}(C_p^{inv} + C_p^{O\&M,fix}) + \sum_{t\in T} C_{p,t}^{run} g_{p,t,r} \\ &+ \sum_{r_2\in R\setminus r}\sum_{p\in P^{transm}\cup P^{H_2\,pipes}} C_{p,r,r_2}^{inv}\, i_{p,r,r_2} + \sum_{p\in P^{ind}\cup P^{transm}}\sum_{t\in T} C_{r,r_2}^{transp} e_{p,t,r,r_2}^{pos} \\ &+ \sum_{p\in P^{plastic}}\sum_{t\in T} C^{st}\, b_{p,t}^{CCS} \end{aligned} \tag{3}$$

where P is the set of all technologies, T is the set of time-steps, and R is the set of the regions. The annualized investment costs, the fixed operational and maintenance costs and the running costs per technology p at time-step t are denoted C_p^{inv}, $C_p^{O\&M,fix}$, and $C_{p,t}^{run}$, respectively. The variable $i_{p,r}$ is the capacity investment per technology p installed in region r, and $g_{p,t,r}$ is the generation of electricity and production of commodities per time-step t and region r, respectively. For the product trade that is transmitted/produced by technologies P^{transm} (the subset of P for transmission lines) and P^{ind} (the subset of P for commodity production units) between regions r and r_2 at per time-step t, the costs C_{r,r_2}^{transp} are considered. The CO_2 emissions $b_{p,t}$ from technology $P^{plastic}$ at time-step t are captured and stored at cost C^{st}.

Equation (4) describes the supply-demand balance. The electricity demand must be satisfied for each time-step t and region r. The electricity balance that matches supply to demand while considering electricity trade between the regions is written as:

$$\begin{aligned} &\sum_{p\in P^{el}} g_{p,t,r} + \sum_{p\in P^{STR}\setminus P^{ind}\cup P^{H_2}} z_{p,t,r}^{dis} \\ &\qquad \geq D_{r,t} + \sum_{p\in P^{ind}} g_{p,t,r} f_p + \sum_{p\in P^{STR}\setminus P^{ind}\cup P^{H_2}} z_{p,t,r}^{ch} + \sum_{r_2\in R\setminus r}\sum_{p\in P^{transm}} e_{p,t,r,r_2}\ , \\ &\forall t\ \in\ T, \forall r\ \in\ R \end{aligned} \tag{4}$$

where P^{el} is the subset of P for all electricity generation technologies. The demand for electricity, $D_{r,t}$, is given per region r and time-step t, the electricity generation $g_{p,t,r}$ per technology p, region r and time-step t, and e_{p,t,r,r_2} is the electricity trade from region r to region $r_2$per time-step t. The charging and discharging of electricity storage technology P^{STR} at time-step t in region r are written as $z^{ch}_{p,t,r}$ and $z^{dis}_{p,t,r}$, respectively. The parameter $f_{p,r}$ describes the electricity demand from the commodity production units P^{ind}.

Equation (5) represents the H_2 balance. Hydrogen is produced in the electrolyser and used to satisfy demand from basic materials industries. Hydrogen can be traded via a pipeline network.

$$g_{P^{Electrolyser},t,r}\eta_p + \sum_{p\in P^{H_2}} z^{dis}_{p,t,r} \geq \sum_{p\in P^{ind}} g_{p,t,r}\, a_p + \sum_{p\in P^{H_2}} z^{ch}_{p,t,r} + \sum_{r_2\in R\setminus r}\ \sum_{p\in P^{H_2\,pipes}} e_{p,t,r,r_2}$$

$$\forall t \in T, \forall r \in R \qquad (5)$$

where a_p is the coefficient applied to relate commodities (ammonia, cement, steel, and plastics) production to H_2 demand for technology $p \in P^{ind}$. The efficiency of electrolyser is written as η_p.

3.4 Terms and definitions

This section defines and explains the terms and key concepts essential to comprehending the research presented in this study.

In the ENODE model, conditions for wind and solar generation are defined by the hourly generation profiles and the land available for solar and wind power. In this work, favourable conditions for wind and solar PV generation are referred to in terms of availability of low-cost electricity generation. Hours with no or low-level generation of electricity from renewable sources are referred to as high net-load hours, and hours during which a large share of the load is covered by renewable electricity generation are low net-load hours. The phrase low-cost access to feedstock is used for regions that produce or distribute feedstock or have low costs for transportation from producer/distributor regions. The capacity utilisation rate indicates how much of the industrial unit is being utilised, i.e., actual output divided by potential output. When the capacity utilisation rate is <100%, it means the plant is not always using its entire installed capacity, i.e., there is an investment in overcapacity to achieve flexibility. The percentage of carbon in the feedstock that ends up in the final products is referred to as the rate of carbon recovery.

The cost of electricity and hydrogen for the basic material industries is calculated according to Equation (6), where the marginal cost ($C^{maginal}_{t,i}$) of electricity or hydrogen (i) per time-step (t) is weighted by the amount of electricity or hydrogen demanded by commodities production units (g_t) in each time-step. The marginal cost of electricity is taken as a proxy for the electricity price and is a result of the modelling, i.e., the marginal value from Eq. (4). The marginal cost of hydrogen is the marginal value of Eq. (5). The marginal value reflects the cost to supply one additional unit of electricity or hydrogen to the energy system.

$$C_i = \frac{\sum_t C^{maginal}_{t,i} g_t}{\sum_t g_t} \qquad (6)$$

4 Main Results

Chapter 4 is organised in the following way. Section 4.1 demonstrates how choice of technological development impacts energy use and CO_2 emissions in a case study of the Swedish steel industry. Section 4.2 shows how large-scale electrification of the basic materials industry influences the origin and composition of electricity generation in the EU. The impact of industry electrification on the cost of the produced commodity and the sizing and location of the electrified industrial units are given in Sections 4.3 and 4.4, respectively. Section 4.5 gives details on the ability of industrial units to vary the CO_2 utilisation modes when electrifying production, i.e., dispatch of the CO_2 utilisation for plastics production and CCS. Section 4.6 presents how an increase in electricity demand from the industry when considering the flexibility options of the electrified industry influences hydrogen production cost.

4.1 The techno-economic pathways towards zero emissions – A Swedish steel industry case study (Paper I)

This section first presents the three pathways obtained from **Paper I** for the timing of replacing current steel production technology and for how energy consumption develops over time. Next, the associated CO_2 emissions are presented.

Production processes mix. Pathway 1 (Figure 4.1a) represents a shift towards using the top gas recycling blast furnace (TGRBF) with carbon capture and biomass for conventional primary steel production and using the EAF with biomass for secondary steel production. Starting in 2025, the production level of iron-ore-based steel will be equivalent to around 40% of the total steel production in Sweden (4.9 Mtonne) owing to the retirement of one blast furnace [86]. By 2030, the primary steel production technology is replaced by a combination of TGRBF and CCS technologies and coal for pulverized coal injection (PCI) is replaced with biomass. CO_2 capture is assumed to use a post-combustion technology.

In Pathways 2 and 3 (Figure 4.1b and c), conventional primary steel production is replaced by the H-DR steel production process, which is assumed to be implemented by 2040 [86]. Between 2025 and 2040, steel is produced in the EAF with biomass at a level corresponding to about 60% of the current total production, which is due to the retirement of one blast furnace in 2025. Starting in 2040, for Pathways 2 and 3, the shares of primary and secondary steel production are assumed to be at the current levels (Figure 4.1, b and c). For Pathway 3 (Figure 4.1c), the export of iron ore pellets is replaced by the export of HBI pellets from 2040. The export of HBI pellets is arbitrarily assumed to reach 6 Mtonnes in 2045. As the iron content of these pellets is higher than that of iron ore pellets, this corresponds to approximately 50% of LKAB’s export of iron ore pellets in 2017.

Energy use. In Pathways 1, 2 and 3 (Figure 4.1, d–f), the replacement of the iron ore-based steel plant by EAF results in reduced coal consumption in 2025. In Pathway 1 (Figure 4.1d), a further decline in the coal demand is observed by 2030, since the PCI into the blast furnace is replaced by biomass. Due to re-injection of the top gas components CO and H_2 (as a reducing agent for the iron ore) into the blast furnace, the total consumption of coke for primary steel production in Pathway 1 is reduced by 27% compared to that in the conventional BF. In 2030, a 44% increase in natural gas consumption is observed relative to the current steel industry configuration, despite the reduction in natural gas consumption achieved through the use of biomass in the EAFs. In the TGRBF/CCS systems, natural gas is utilised to preheat the steam, as well as to meet the supplemental thermal energy demand of the CCS technology [139].

For Pathway 2 (Figure 4.1e), the demand for fossil fuel-based energy carriers, such as coke, coal, oil and natural gas, decreases by almost 100% by 2040, as compared to the demand linked to the current steel process configuration. However, in the period 2025–2040, the demand for fossil fuel-based energy carriers in Pathway 2 is higher compared to that in Pathway 1. Electricity use increases significantly, implying a need for electricity of around 12 TWh per year in 2045. For Pathway 3 (Figure 4.1f), the energy consumption level is similar to Pathway 2 until 2040 when the consumption of electricity increases dramatically, to reach 33 TWh per year by 2045.

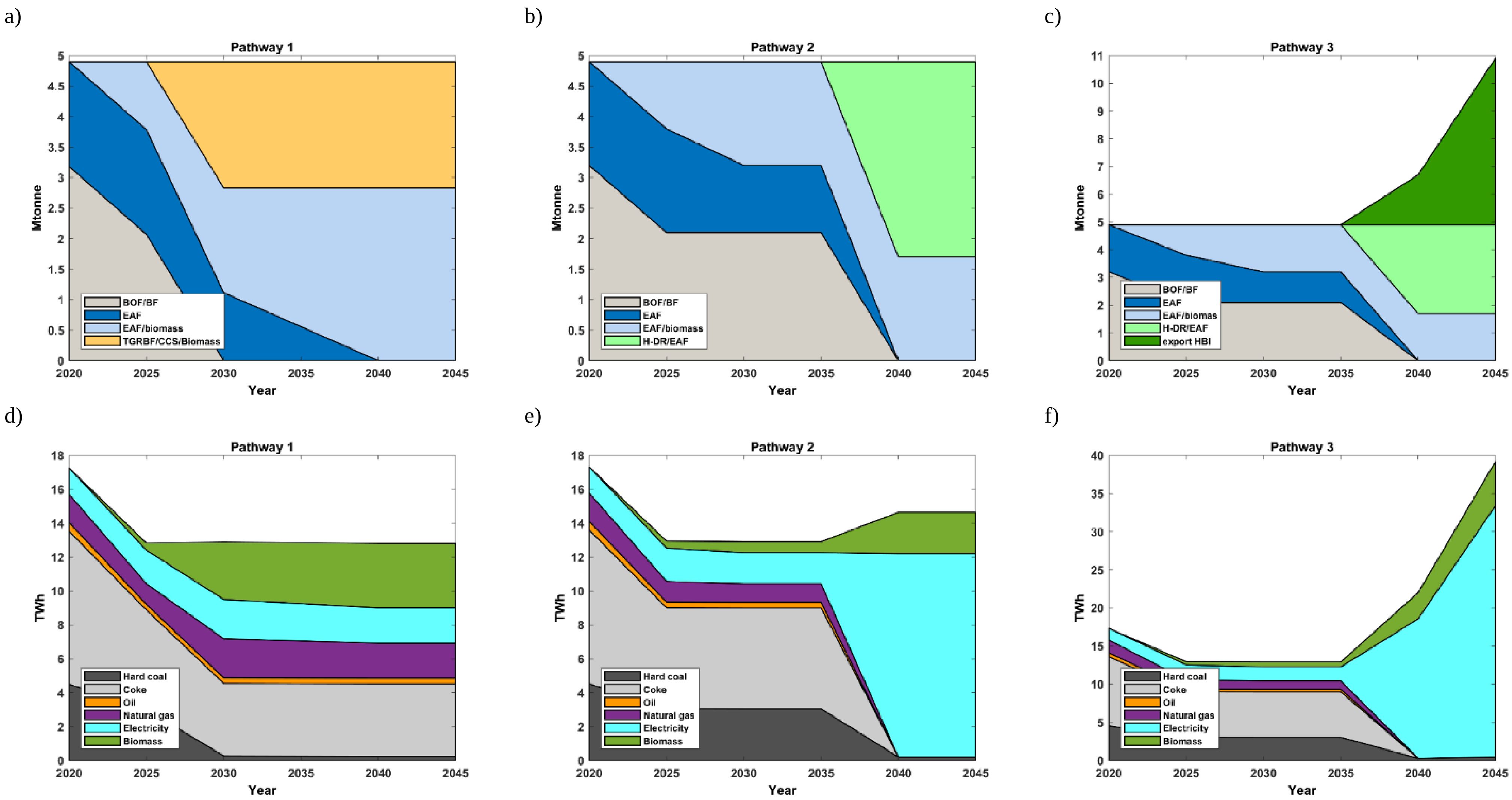


Figure 4.1: Summary of the results from the case study in **Paper I**. Production processes mix (a–c) and energy use (d–f) for the Swedish steel industry pathways from 2020 to 2045. Note the different scales of the y-axis in panels c and f. [Source: Figures 2 and 3 in **Paper I**].

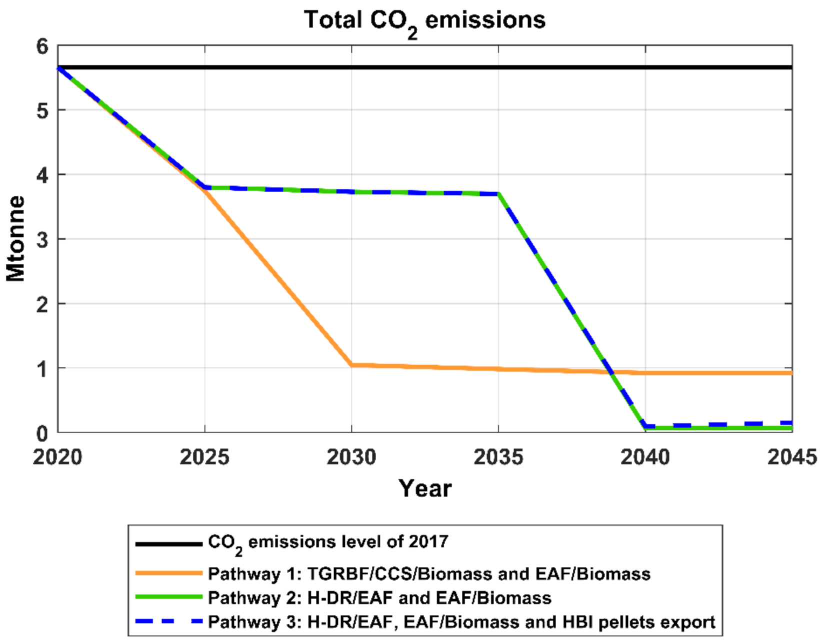


Figure 4.2: Development of CO_2 emissions levels for the Swedish steel industry pathways from 2020 to 2045. [Source: Figure 7 in **Paper I**].

The pathways in relation to the CO_2 emission targets. As shown in Figure 4.2 already in 2030, Pathway 1 yields an 80% reduction in CO_2 emissions when applying CCS in combination with biomass substitution in the blast furnace, together with replacing an iron-ore-based steel plant with an EAF. However, only an 83% reduction in CO_2 emissions from steel production can be obtained for Pathway 1. Pathways 2 and 3, which include electrification, enable further reductions in emissions compared to implementing CCS and using biomass.

For all the investigated pathways, scrap metal consumption should increase starting in 2025 due to the replacement of BF/BOF with EAF. A global increase in scrap metal availability is expected due to steel stocks building up in emerging economies [140], while availability in the EU will stabilise, as the steel stock becomes saturated [141]. In this context, it should be important to prioritise innovation and technological developments related to delivering the highest quality of steel from recycling (EAF) (see for example [61]).

The development of today's Swedish steel and iron industry leans towards electrification as expressed by Pathways 2 and 3 in **Paper I**. Sweden has an ongoing demonstration project with hydrogen-based steel production in the form of the HYBRIT project [142]. The first batch of green hydrogen-based steel was produced and delivered to a customer already in the summer 2021 [143,144]. In 2021, the Swedish venture H2 Green Steel (H2GS) announced that they will develop hydrogen-based steel production in Sweden too. Production is slated to begin in 2025 (which requires rapid H-DRI/EAF technology development, assuming its TRL 7 (2028-2030) [145,146]), and by 2030, H2GS plans to have an annual production capacity of five million tonnes of high-quality steel [147]. The Swedish case study helps inform our understanding of the characteristics of the steel industry's transition to deep decarbonisation, since Sweden seems to have the most advanced initiatives for hydrogen-based steel production. However, decarbonisation of the steel industry will take different forms in different countries, depending on the local characteristics. The conditions for renewable electricity, the availability of biomass and CO_2 storage sites for CCS options, and ambitions regarding the energy transition will all significantly affect the feasibility of decarbonisation options. Thus, the timing and rate of emission reductions will vary depending on the prevailing conditions in each country.

Key message. **Paper I** explores the possible pathways for deep CO_2 emission reductions in the Swedish steel industry by 2045, comparing alternative pathways to current technologies. The technological assessment shows that the combination of top gas recycling blast furnace (TGRBF)/CCS with biomass for primary steel production and electric arc furnace (EAF) with biomass for secondary steel production can achieve an 80% reduction in CO_2 emissions already by 2030. The electrification of primary steel production through hydrogen, as applied in Pathway 2, would facilitate a further reduction in CO_2 emissions from steel production as compared to Pathway 1 but would require an additional electricity demand of almost 14 TWh in 2045. Pathway 3 proposes increased production of HBI pellets, leading to abatement of emissions from the steel industry outside Sweden, albeit with a significant increase in electricity demand (25.6 TWh) and new investments in Swedish steel production capacities. The main drivers for Pathways 2 and 3 in the modelling are low-cost, fossil-free electricity and low-cost access to iron ore in Northern Sweden.

4.2 Implications for the electricity system from the electrification of industry (Paper V)

Scenario descriptions. To show the impacts of the industrial flexibility options (Section 2.4) on the electricity system, seven scenarios were investigated (Figure 4.3). Three parameters (operational flexibility, trade of commodities, and CO_2 utilisation) represent the flexibility options (flexibility in time and location and flexibility in CO_2 utilisation) that can be applied to varying degree in the production processes of commodities. The *Flex* scenario considers all industrial flexibility options investigated in this work (*cf*. Section 2.4).

Flexibility in time is defined by operational flexibility, i.e., the ability of the industrial unit to vary the output within the load ranges. In the *Inflex_time* scenario ("inflex" for inflexibility), all industrial units operate continuously and have a capacity utilisation rate of close to 100%. Flexibility in location is defined by the ability to export commodities. With flexibility in location, the model provides the optimised geographical location of industries; it is possible to allocate industrial units to regions without existing industry, increase commodities production in the regions with existing industry, and dissociate parts of the electrified industry supply chains. The *Inflex_location* scenario is the scenario with limited flexibility with regards to location, i.e., trade of waste is not allowed. Flexibility in CO_2 utilisation is used to describe the ability of industrial units to vary the CO_2 utilisation modes, i.e., CO_2 usage for commodities (i.e., methanol) production and CCS. If only one square under the parameter 'CO_2 utilisation' is marked in grey, this means that only CCU as in the *Inflex_CO_2(CCU)* scenario or CCS as in the *Inflex_CO_2(CCS)* scenario can be used to utilise CO_2 emissions if available.

All the flexibility options are limited in the *Inflex_location_time_CO_2(CCU)* and *Inflex_location_time_CO_2(CCS)* scenarios.

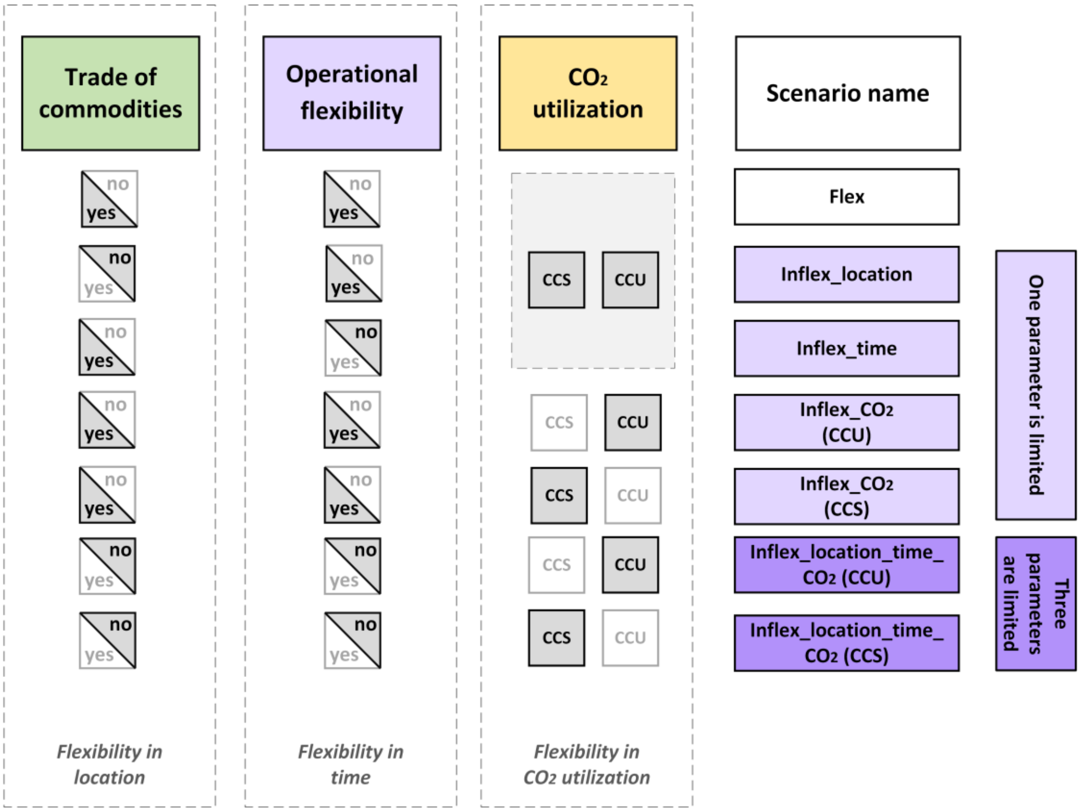


Figure 4.3: Schematic overview of the parameters that define the investigated scenarios.

Electricity generation. Figure 4.4 shows the electricity generation mix of the EU regions without electrified industry (left-hand panels), i.e., the generation mix which can meet the present electricity demand (i.e., present hourly demand profiles obtained from ENTSO-E, see Section 3.1) and an assumed electricity demand from the transport and heat sectors. Figure 4.4 also shows the changes in electricity generation as industrial electricity demand is introduced for the different scenarios (Figure 4.3). Only electricity generation technologies with net-zero CO_2 emissions are allowed.

Figure 4.4 shows that the additional electricity demand is met primarily by wind, solar, and nuclear power in the EU, and all modelled scenarios require a substantial and rapid increase in electricity generation capacity.

As illustrated in Figure 4.4, for the scenarios without industrial flexibility options (*Inflex_location_time_CO₂(CCS)* and *Inflex_location_time_CO₂(CCU)*) as well as for those without flexibility in time (*Inflex_time*), nuclear power plays an important role in supplying the electricity demand, i.e., electricity generation from nuclear power covers around 20% of the total demand in these scenarios. With limited flexibility in time, as applied in the *Inflex_time*, *Inflex_location_time_CO₂(CCS)*, and *Inflex_location_time_CO₂(CCU)* scenarios, electricity generation based on biogas increases, since it compensates for the lack of temporal flexibility on the demand side.

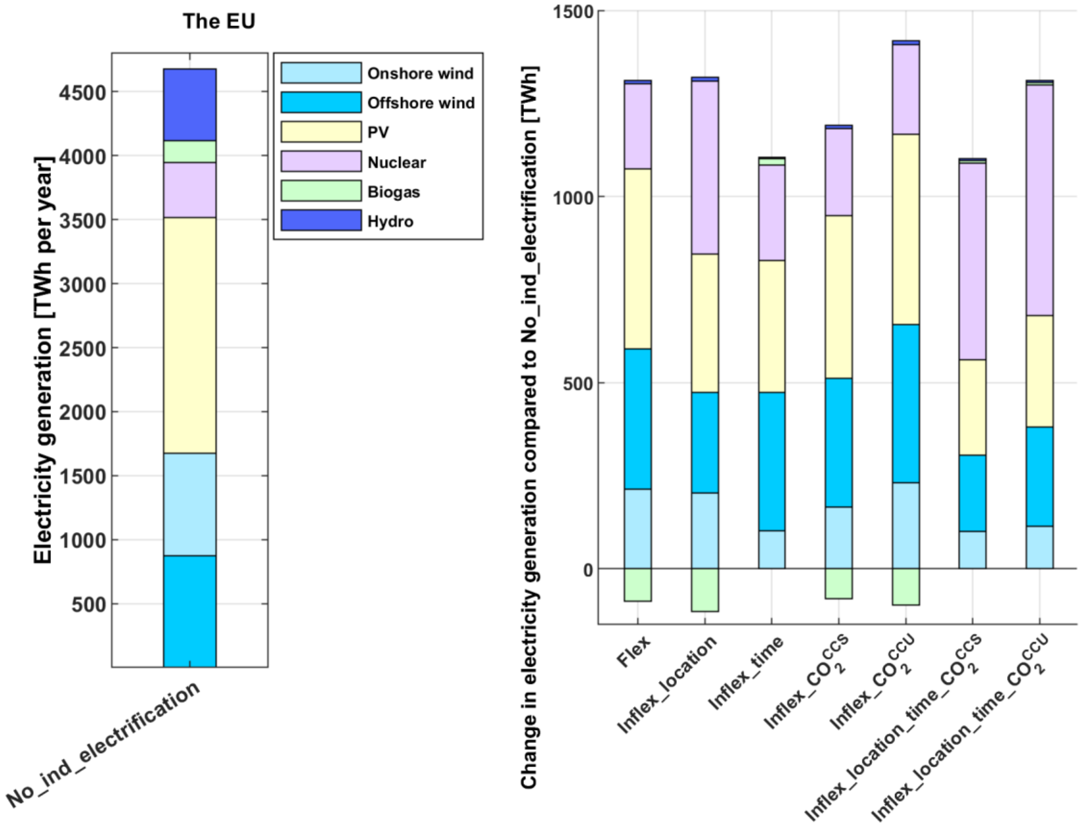


Figure 4.4: Total annual electricity generation which can meet the present electricity demand and an assumed electricity demand from transport and heat sectors and the change in electricity generation relative to the case without electrification of the industry (i.e., ammonia, cement, steel, and plastics industries (right-hand panel)) for the investigated regions.

The limitation as to CO_2 utilisation flexibility when all the CO_2 emissions released are used to produce plastic, as applied in the *Inflex _CO₂(CCU)* and *Inflex_location_time_CO₂(CCU)* scenarios, provides the largest increase (28%) in electricity generation compared to an electricity system without electrified plastics production (*No_ind_electrification* scenario). When all the CO_2 emissions released are captured and stored (*Inflex _CO₂(CCS),* and *Inflex_location_time_CO₂(CCS)),* the increase (24%) in electricity generation relative to the *No_ind_electrification* scenario is instead the lowest among all the scenarios investigated.

The combination of the industrial flexibility options, as applied in the *Flex* scenario, allows for the highest deployment of wind and solar power capacity in the European future electricity system as compared to the rest of the scenarios. However, the *Flex* scenario also results in the highest investment costs for battery capacity among the investigated scenarios. Despite incurring additional costs from investments in flexibility measures on both the electricity supply side (battery capacity) and demand side (overcapacity of the industrial units and hydrogen storage), the *Flex* scenario has the lowest total system cost.

Key message. The total annual level of electricity generation in the geographical area investigated (i.e., the EU27 (excluding Cyprus and Malta, Great Britain, Norway, and Switzerland) needs to be in the range of 5,800–6,000 TWh to meet the future demand, i.e., including the present electricity demand and the new electricity demands from transport, heat, and industry, for the scenarios investigated in this work.

With industrial flexibility, the additional electricity demand is met mainly by production from wind and solar power, while it reduces the production of electricity from biogas generation technologies, as compared to the case without industrial flexibility. The electricity demand from electrified industry that operates without flexibility is primarily met by nuclear power. There is an obvious need to accelerate the deployment of electricity generation technologies if the EU targets regarding climate neutrality are to be achieved by 2050.

4.3 Impacts of the industrial flexibility options

4.3.1 Operational time and operational level of the industrial capacity (**Paper II**)

This section shows how electricity price variations impact the operation of the industrial units (which can follow electricity price variation, i.e., have flexibility in time) for the example of the steel production process. Details for the assumed design of the electrified steel production process via hydrogen direct reduction are given in Section 2.3.

Scenario descriptions. Hourly electricity price profiles for 2050, representing two regions with different conditions for renewable electricity (southern Germany and northern UK) are inputs defining scenarios in this section. The electricity price profiles are derived from the electricity system investment model H2D (see Section 2.5 for details).

Figure 4.5 and Figure 4.6 show levels of electricity production from wind and solar power, together with the electricity price profiles (Figure 4.5, a and d; and Figure 4.6, a and d); hydrogen production and HBI pellets production and state of charge of the hydrogen storage (Figure 4.5, b and e; and Figure 4.6, b and e); steel production and state of charge HBI storage (Figure 4.5, c and f; and Figure 4.6, c and f) in 2050, for southern Germany and Scotland, respectively

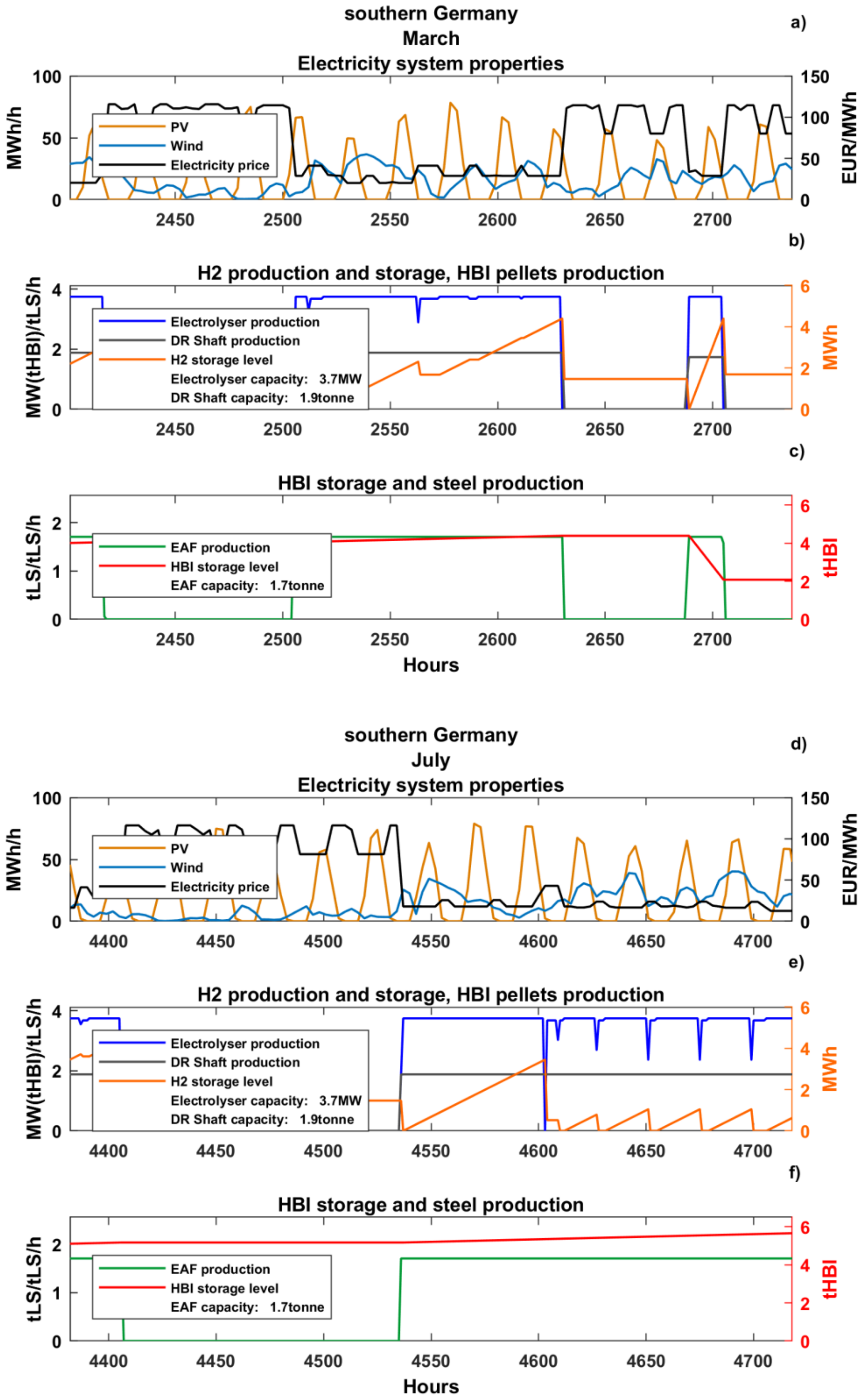


Figure 4.5: Wind and solar power production, electricity price profiles (a, d); production levels of electrolyser and DR shaft furnace, state of charge of hydrogen storage (b, e); production levels of EAF and state of charge of HBI storage (c, f), in southern Germany for two weeks in March (upper plots) and in July (lower plots) in future year (2050). [Source: Figure 6 in **Paper II**].

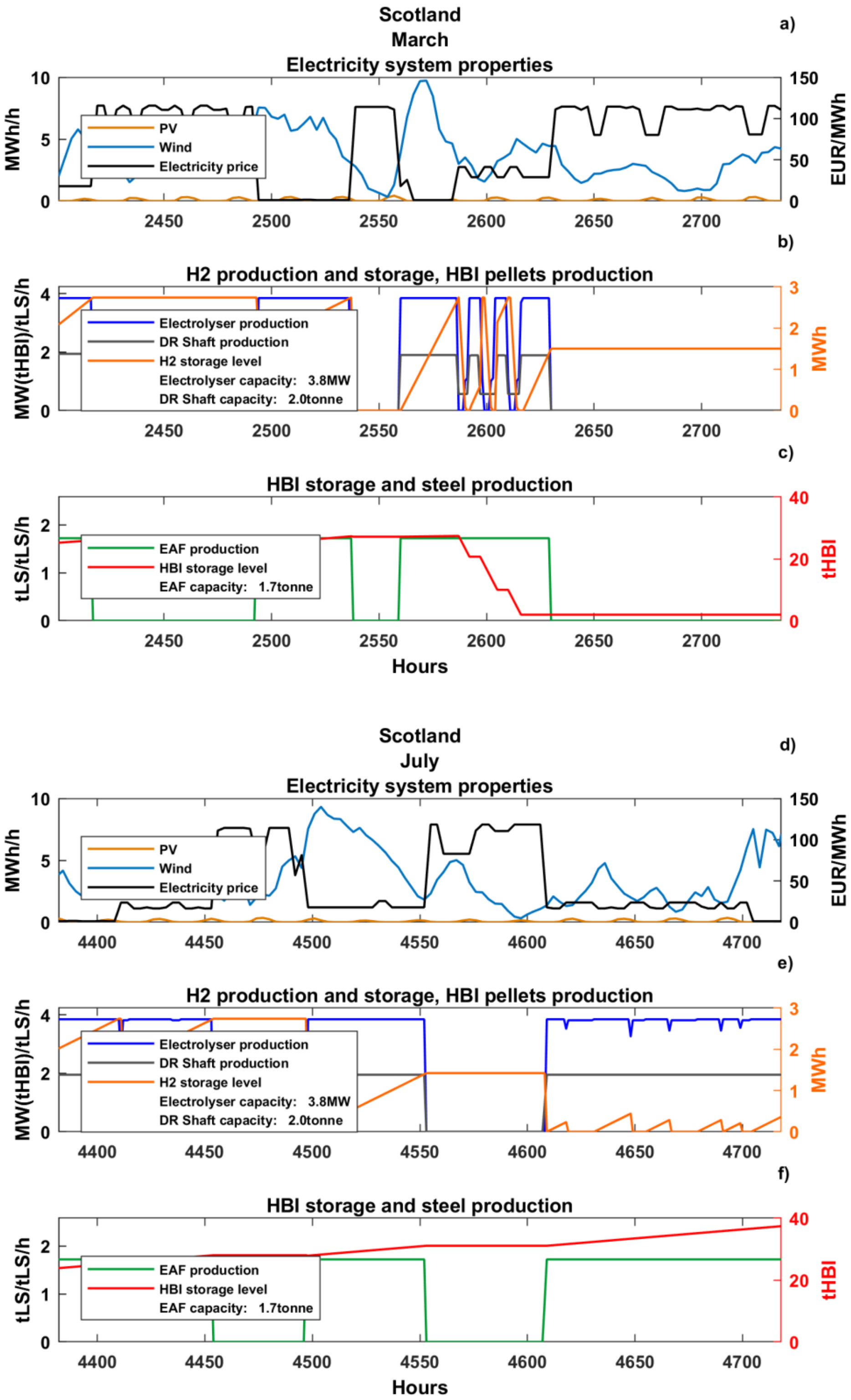


Figure 4.6: Wind and solar power production, electricity price profiles (a, d); production levels of electrolyser and DR shaft furnace, state of charge of the hydrogen storage (b, e); production levels of EAF and state of charge of HBI storage (c, f), in Scotland for two weeks in March (upper plots) and in July (lower plots) in future year (2050). [Source: Figure 7 in **Paper II**].

In Germany (Figure 4.5), the operation of the steel production units follows the solar-influenced electricity price variations as shown for both March (Figure 4.5a) and July (Figure 4.5d). The largest consumer of electricity in the steelmaking process, the electrolyser, avoids hydrogen production when the electricity price exceeds 50 €/MWh, as shown in Figure 4.5, b and e. The electrolyser produces at full capacity when the electricity price is less than 50 €/MWh and hydrogen flow is used both for charging the hydrogen storage and for reduction within the DR shaft furnace. During long periods of high solar radiation and good wind conditions, such as in July, the electrolyser sometimes operates at reduced capacity to avoid peaks even during low-price hours, i.e., Hours 4600–4700 in Figure 4.5e. The continuous production of the DR shaft furnace during such periods is supported by discharging stored hydrogen. Unlike the electrolyser, the EAF occasionally operates at full capacity even when the electricity price exceeds 50 €/MWh, i.e., Hours 2680–2700 in Figure 4.5c. The DR shaft furnace operates at reduced capacity when the electricity price fluctuates at levels above 50 €/MWh, and as the level of production from the DR shaft furnace is not sufficient to support EAF production at full capacity, HBI storage is discharged (Hours 2680–2700 in Figure 4.5c).

A comparison of Figure 4.5 and Figure 4.6 illustrates that the difference in the electrolyser operation between southern Germany and Scotland is due to the difference in the number of low electricity price periods and their distribution over the year. The wind-dominated Scotland region has a larger number of low electricity price periods than the solar-rich southern Germany. In southern Germany, the electrolyser reduces operation when electricity price varies between 40 and 50 €/MWh (Hours 4600-4700 in Figure 4.5f), while in Scotland, the electrolyser stops production if electricity price exceeds 40 €/MWh (Hours 2550-2600 in Figure 4.6a). In Scotland, the EAF produces at full capacity, taking advantage of the low electricity price (Figure 4.6f). The continuous production of the EAF during such periods, when the DR shaft furnace operates at reduced capacity, is supported by discharging HBI storage. The HBI storage capacity is almost ten times greater in Scotland than in southern Germany, since the variability of wind power, with a typical duration of several days up to a week, dominates the electricity system in Scotland.

Key message. The investments in and operation of the industrial units depend on the electricity system composition. The results from **Paper II** indicate that steel production units (electrolyser, DR shaft furnace and EAF) and storage systems (HBI and hydrogen) are sized to manage wind variations for up to several days for the wind-dominated region and diurnal solar variations for the solar PV-dominated region. Based on the modelling, the largest consumer of electricity within the steel production process, the electrolyser, avoids hydrogen production when the electricity price exceeds 50 €/MWh.

4.3.2 Methods for commodity production cost estimation (**Papers I–III** and **V**)

The cost of commodities production will be affected by the electrification of the industries. In this section, the advantages and disadvantages of different methods to provide insights into the production costs of commodities are analysed based on the results obtained in **Papers I–III** and **V**. Steel is used as an example of a commodity for which the production is electrified. Insights into the production cost characteristics are provided in terms of the distributions of the annualised investment costs, fixed O&M costs, electricity costs, and transportation costs.

Methods to account for commodities production costs. Table 4.1 shows the main characteristics, limitations and novelty of the methods used to calculate cost of steel production in **Papers I–III** and **V**. For a future electricity system with a high share of VRE and an electrified steel industry, disregarding the impacts of the electricity system (as in **Paper I**), i.e., investments in over-capacity and hydrogen and HBI storage units, when assessing the cost of steel production can lead to an over-estimation of the costs for electricity and an under-estimation of the investment cost. The method used to calculate the steel production cost applied in **Paper II** captures the effects of the electricity system composition and related electricity cost variations on the electrified steel industry but does not consider future investments in electricity generation technologies. In **Paper III**, the mutual impacts of the electricity system and the electrified steel industry are investigated. The low cost of electricity can be exaggerated for the steel industry, the production level of which follows electricity price variations, since more than one sector can be electrified in the future electricity system. In **Paper V**, the electrification of several basic materials industries (ammonia, cement, steel, and plastics) is studied. The cost for hydrogen experienced by the steel industry is taken as the demand-weighted hydrogen price, where the marginal cost of hydrogen is a result of the modelling, i.e., the marginal value derived from Eq. (5). In **Paper V**, over-investments in the capacity of the electrolyser and the capacity of hydrogen storage, as well as the operational cost of the electrolyser are not defined for each industry.

Table 4.1: Main characteristics of the methods used to calculate steel production cost.

	Method	**Impacts considered in this work**			**Main limitations**	**Novelty**
		Electricity system on electrified industry	*Electrified industry on electricity system*	*Electrification of more than one industry*		
Paper I	Techno-economic pathways	no	no	no	Investments in storage systems (i.e., H_2) and investments in over-capacity are not accounted for; average electricity price	Future pathways to reach zero CO_2 emissions in the Swedish steel industry are analysed
Paper II	Steel process optimisation model	yes	no	no	Investments in electricity generation technologies are not considered	The flexibility in time of industry is considered
Paper III	Electricity system optimisation model	yes	yes	no	Electricity costs for steel industry are under-estimated	The electricity system feedback on the introduction of electrified industry (taking into account flexibility options) is considered
Paper V	Electricity system optimisation model	yes	yes	yes	Demand-weighted hydrogen cost, i.e., over-investments in capacity of the electrolyser and capacity of the hydrogen storage are undefined for each industry	The combined effects of electrified energy-intensive basic materials industries are considered

Steel production cost. Figure 4.7 shows the breakdown of the production cost per tonne of steel for the methods applied in **Papers I–III** and **V**.

Scenario descriptions. The steel production cost for the scenario in which the Swedish steel industry is electrified through the use of a hydrogen direct reduction process is taken from **Paper I** (see Pathways 2 and 3 in **Paper I**). The steel production cost for the scenario with the electricity price profile of Southern Germany for Year 2050 is taken from **Paper II** (see scenario *DE 2050* in **Paper II**). The steel production cost for **Paper III** is derived from the scenario that has flexible operation of steel production units with the export of commodities being allowed (see *Main_Penalty_50* scenario in **Paper III**). The steel production cost from **Paper V** is taken from the scenario with the cost-efficient geographical location of the parts of the electrified industries' supply chains (without hydrogen export) and flexible operation of industrial units (see the *Optimised_location* scenario in **Paper V**).

The steel production cost is divided into the feedstock costs (i.e., iron ore), annualised investment cost, fixed O&M costs, cost of electricity, transportation costs, and hydrogen cost. In **Papers I–III**, the cost of hydrogen is calculated as the sum of variable operating costs (i.e., electricity cost, the fixed operating costs, and the annualised capital costs for the electrolyser and hydrogen storage). In **Paper I**, an average electricity price for Sweden for the period of 2012–2019 of 35 €/MWh is used. The electricity price profile (Southern Germany, Year 2050) obtained from the electricity system investment model H2D [116] is taken as the input in **Paper II**. In **Papers III** and **V**, the cost of electricity as experienced by the steel industry is taken as the demand-weighted electricity price, where the marginal cost of electricity is taken as a proxy for the electricity price and is a result of the modelling, i.e., the marginal value from Eq. (4). The marginal value reflects the cost to supply one additional unit of electricity to the energy system. In analogy, the cost of hydrogen in **Paper V** is taken as the demand-weighted hydrogen price for which the marginal cost of hydrogen from the modelling is used as a proxy (i.e., the marginal value derived from Eq. (5)).

The cost of feedstock, i.e., iron ore, accounts for the largest share (41%–53%) of the steel production cost, followed by the cost of hydrogen (19%–36%) (Figure 4.7). Without considering the impact of electrified industry on the electricity system, as applied in **Papers I** and **II**, the electricity cost (i.e., for steel production units, the DR shaft furnace and EAF; the electricity and investment costs for the electrolyser are included in the hydrogen cost) represents the third-largest share of the steel production cost.

When the mutual impacts of the electrified industry and electricity system are considered, i.e., investments in both electricity generation technologies and industrial units are optimised, the weighted electricity cost for steel production units decreases, despite required investments in new electricity generation technology, which affect the cost of electricity generation. The introduction of the electrified steel production process into the electricity system, as applied in **Paper III**, leads to investments in wind and solar power to satisfy the new electricity demand. In **Paper III**, flexible operation of the electrified steel production results in the absorption of low-cost electricity, such that the electricity cost (and, consequently, the hydrogen cost) is lower in comparison to the costs obtained in **Papers I** and **II**.

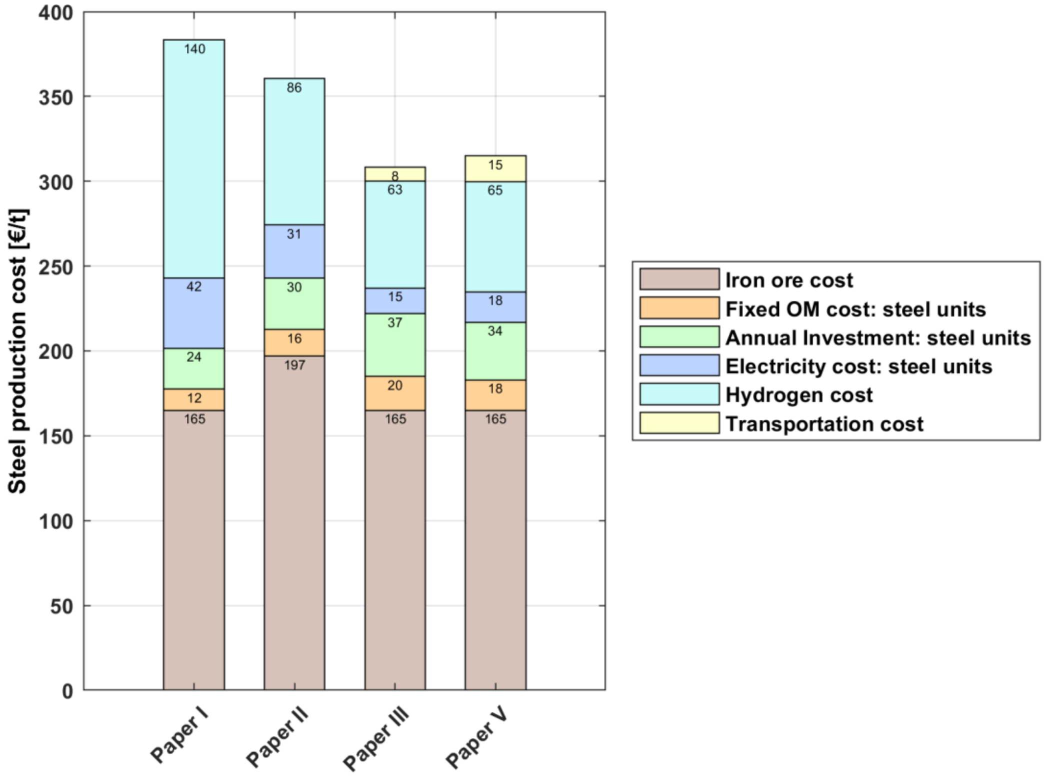


Figure 4.7: Breakdown of the modelled production cost per tonne of steel for **Papers I–III** and **V**. The costs are divided into feedstock costs, cost of capture and storage of CO_2, annualised investment cost, fixed O&M costs, electricity cost, transportation costs, and hydrogen costs. Steel units are a direct reduction shaft furnace and an electric arc furnace.

Electrification of several industries, as applied in **Paper V**, increases the hydrogen costs (electricity and investment costs of the electrolyser) by 3% and increases the electricity cost by 17% as compared with the hydrogen cost obtained in **Paper III**. The increases in electricity and hydrogen costs are attributed to the expansion of the electricity demand, resulting in the exhaustion of available resources for VRE sources. In addition to the present electricity demand and electricity demand from steel considered in **Paper III**, the electricity demands from transport, heat, ammonia, cement, and plastics industries are included in **Paper V**. The most-flexible consumer (ammonia industry) absorbs electricity during the hours with the lowest electricity price, while the less-flexible consumers (e.g., steel industry) consume electricity at a higher price but instead avoid high-cost periods. Being the "first" large-scale flexible electricity consumer in a future zero-emissions electricity system confers the greatest benefits.

Key message. Several methods to calculate commodities production costs are defined. The method chosen depends on the research question being addressed. This section shows the importance of accounting for the interactions between the electricity system and several new electricity demand categories. It is crucial for stakeholders to understand the implications of these methodological choices, so as to make informed decisions.

4.3.3 Plastics production cost (**Papers IV** and **V**)

This section presents how industrial flexibility options affect commodities production costs for the example of plastics. The details of the method applied to calculate commodity production cost are given in Subsection 4.3.2. Figure 4.8 shows the breakdown of the plastics production cost per tonne of plastic for the seven scenarios introduced in Section 4.2 (*Flex*, *Inflex_Time*, *Inflex_Location*, *Inflex _CO_2(CCS)*, *Inflex_CO_2(CCU)*, *Inflex_location_time_CO_2(CCS)*, *Inflex_location_time_CO_2(CCU)*. The cost is divided into the feedstock costs (i.e., plastic waste and waste), cost to capture and store CO_2, the annualized investment cost, the fixed operations and maintenance costs (O&M) costs, the cost of electricity, and the transportation costs. As mentioned in Section 3.4, the cost of electricity as experienced by the producer of the plastics is here taken as the consumption-weighted electricity price (*cf*. Eq.(6)).

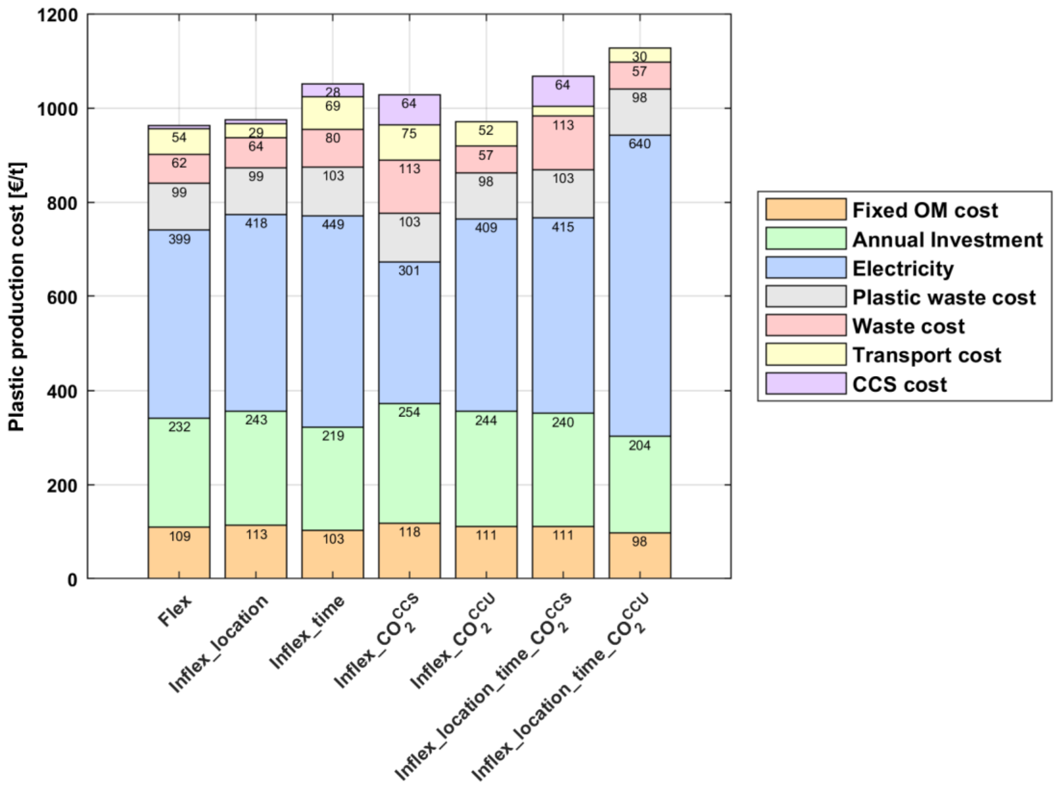


Figure 4.8: Breakdown of the modelled cost of plastics production into feedstock costs, cost of capture and storage of CO_2, the annualized investment cost, the fixed O&M costs, electricity cost, and transportation costs for the seven scenarios. [Source: Figures 3 in **Paper IV]**.

The plastics production cost is in the range of 960–1,130 €/t for the investigated scenarios (Figure 4.8). The cost of electricity is the largest cost in all the scenarios, followed by the annualized investment cost. The *Flex* scenario with full flexibility, i.e., flexibility of time and location and flexibility of CO_2 utilisation, yields the lowest cost for plastics production (€960 per tonne). The *Flex* scenario has the highest carbon recovery rate and the lowest CCS cost among the scenarios with flexible CO_2 utilisation (*Inflex_Time*, *Inflex_Location*).

The highest increase in plastics production cost is observed for the scenarios in which the plastics production units cannot shift the electricity consumption in time (*Inflex_Time*, *Inflex_location_time_CO_2(CCS)*, *Inflex_location_time_CO_2(CCU)*) as compared to the *Flex* scenario.

In the *Inflex_time* scenario, flexibility in CO_2 utilisation compensates for the limitation of the flexibility in time to avoid high electricity price hours, i.e., there is an increase in the CCS cost compared to the *Flex* scenario.

The *Inflex_CO₂(CCU)* scenario increases the value of the flexibility in time compared to the *Flex* scenario due to an increase in the demand for electricity.

In *Inflex_CO₂(CCS)* and *Inflex_location_time_CO₂(CCS)*), more feedstock needs to be processed to recover the required amount of carbon; thus, a larger cracker size (high investment cost of 240–254 €/t) is needed than in the scenarios without CO_2 utilisation limitations. In addition, overinvestment occurs to avoid high electricity price hours for the plastics production units.

When flexibility in location is limited (the *Inflex_location* scenario) investment costs increase by 5% as compared to in *Flex*. The overinvestment in plastics production capacity is made to avoid electricity consumption during high-net-load events, i.e., flexibility in time compensates for the limited flexibility in location.

Without industrial flexibility options, a high CO_2 utilisation rate, as applied in the *Inflex_location_time_CO₂(CCU)* scenario, results in the highest cost for electricity, with the highest total production cost as a consequence. Without the flexibility options but with a low CO_2 utilisation rate, as in *Inflex_location_time_CO₂(CCS)*, the plastics production cost is lower than in the *Inflex_location_time_CO₂(CCU)* scenario, which means that without industrial flexibility options, it is more cost-effective to capture than to use CO_2 emissions.

The transportation costs for commodities related to the plastics industry (here: waste, plastics waste, methanol, and plastics) in **Paper IV** differ from those in **Paper V** due to assumptions made on plastics demand. In **Paper IV**, current (2020) demand for plastics in the investigated regions is applied as the regional *plastic* demand. In **Paper V**, the current production of plastics is instead used as the regional demand for *commodities* to reflect the connection of the basic materials industry to the location of other industries. Due to this assumption on demand for plastics, transportation costs are higher in **Paper IV** compared to **Paper V**.

Key message*:* Full flexibility (flexibility with regards to time and location, and flexibility of CO_2 utilisation) of the plastics production process yields: 1) the lowest cost for plastics production; 2) the highest rate of carbon recovery from the feedstock among the scenarios that lack any limitation as to CO_2 utilisation; and 3) the lowest capacity utilisation rate, i.e., there is an investment in over-capacity to achieve flexibility. Time flexibility is found to have a stronger impact on the cost of plastics than locational flexibility or flexibility in relation to CO_2 utilisation. Scenarios with time flexibility limitations exhibit the highest costs for the production of plastics among the scenarios investigated.

4.4 Locations and sizes of industrial units - impact of flexibility in location (Papers III–V)

Electrolyser. A climate-neutral economy is expected to rely heavily on hydrogen, since it enables emissions-free transportation, heating, and industrial activities, as well as energy storage, albeit with a requirement for large amounts of electricity. The European Commission aims to build 40-GW electrolysers within the EU by Year 2030, to produce up to 333 TWh of hydrogen from renewable electricity (mainly solar and wind power) [148].

The modelling results for the total investments in electrolysers to satisfy the hydrogen demand from electrified industry in the EU are in the range of 50–135 GW, while the annual hydrogen production from electrolysers is in the range of 460–740 TWh for the investigated scenarios (see Section 4.2 for details). The lowest electrolyser capacity of 50 GW is seen in the scenario with limited time flexibility, when the electrolyser utilisation ratio is 100%. Investments in electrolyser over-capacity, despite the capital cost increase, reduce the cost for electricity to produce commodities, which implies that the total cost of the commodities decreases (see Section 4.3).

Figure 4.9 shows the modelling results for the sizes of the electrolyser for seven scenarios - *Flex*, *Inflex_location*, *Inflex_time*, *Inflex_CO_2(CCS)*, *Inflex_CO_2(CCU)*, *Inflex_location_time_CO_2(CCS)* and *Inflex_location_time_CO_2(CCU)* [see Section 4.2], in six regions - Northern Sweden (SE_N), Southern Poland (PO_S), Eastern Spain (IB_E), Southern Italy (IT_S), Austria, Czech Republic and Slovakia (ATCZSK) and Scotland (UK_N). The electrolyser capacity is presented in GW.

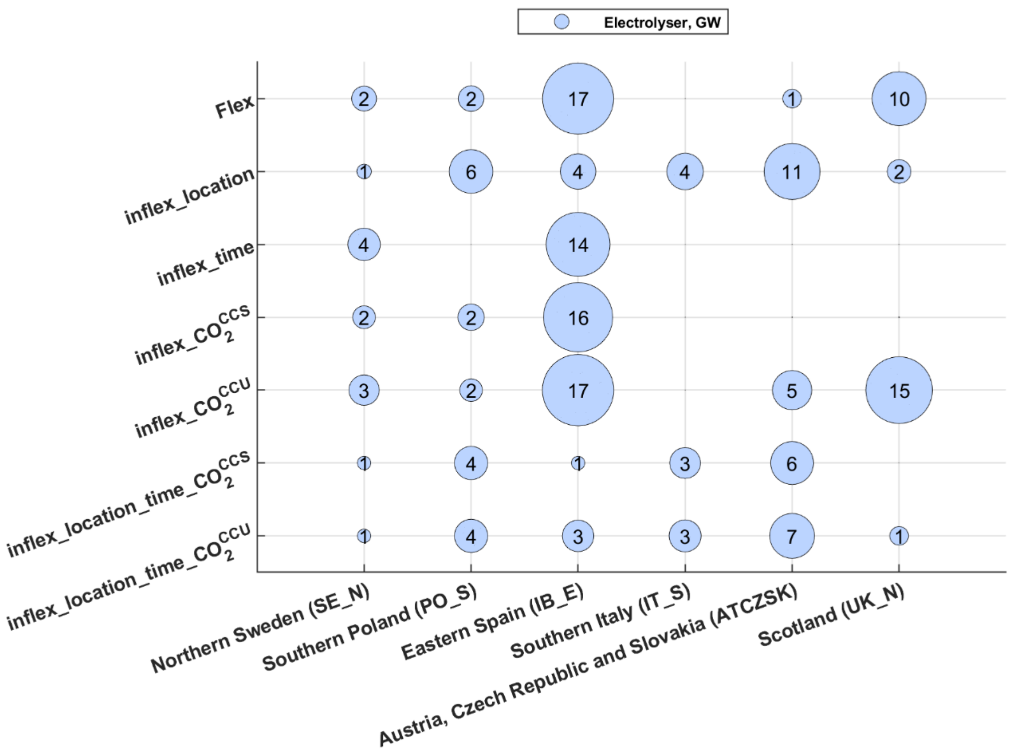


Figure 4.9: The electrolyser capacities (in GW) for Northern Sweden (SE_N), Southern Poland (PO_S), Eastern Spain (IB_E), Southern Italy (IT_S), Austria, Czech Republic, and Slovakia (ATCZSK), and Scotland (UK_N) (*x*-axis) for the investigated scenarios (*y*-axis).

In the *Inflex_location*, *Inflex_location_time_CO_2(CCS)*, and *Inflex_location_time_CO_2(CCU)* scenarios, the localisation of the electrolyser capacity is determined exogenously to the regions with ammonia, steel, and plastics production (i.e., at the locations of the industries that require hydrogen in their production processes). For the *Inflex_location* scenario, the total electrolyser capacity in the EU regions investigated in this work is double that in the *Inflex_location_time_CO_2(CCS)* and *Inflex_location_time_CO_2(CCU)* scenarios, which are scenarios with the lowest possible size of the electrolyser, meaning that it is cost-efficient to increase the capacity of the electrolyser in regions with existing industry, so as to follow the electricity price variations.

In the scenarios with flexibility in location, i.e., the optimised location of the industries (*Flex*, *Inflex_tim*e, *Inflex_CO_2(CCS)*, and *Inflex_CO_2(CCU)* scenarios) the electrolyser capacities move to the regions that have access to low-cost electricity and existing industry (SE_N, IB_E and UK_N), as compared with the *Inflex_location* scenario. When there is limited flexibility with respect to time and optimised location (*Inflex_time* scenario), the electrolyser capacity is concentrated to those regions that have a low average electricity cost (SE_N and IB_E). For the scenarios with limited flexibility in relation to CO_2 utilisation, when all the CO_2 emissions from the process are captured and stored [*Inflex_CO_2(CCS)* and *Inflex_location_time_CO_2(CCS)*] there is no demand for hydrogen from the plastics industry, so there are no investments in electrolyser capacity in the regions with a demand for hydrogen only for plastics production [Scotland (UK_N)].

Key message: With flexibility in location, the electrolyser capacity is built in those regions that can produce hydrogen at the lowest cost; these tend to be regions with good conditions for wind and solar power. The optimised location of the electrolyser capacity takes advantage of the differences between regions in relation to resource availability for low-cost wind and solar power; as a result, the differences in electricity prices between regions are evened out.

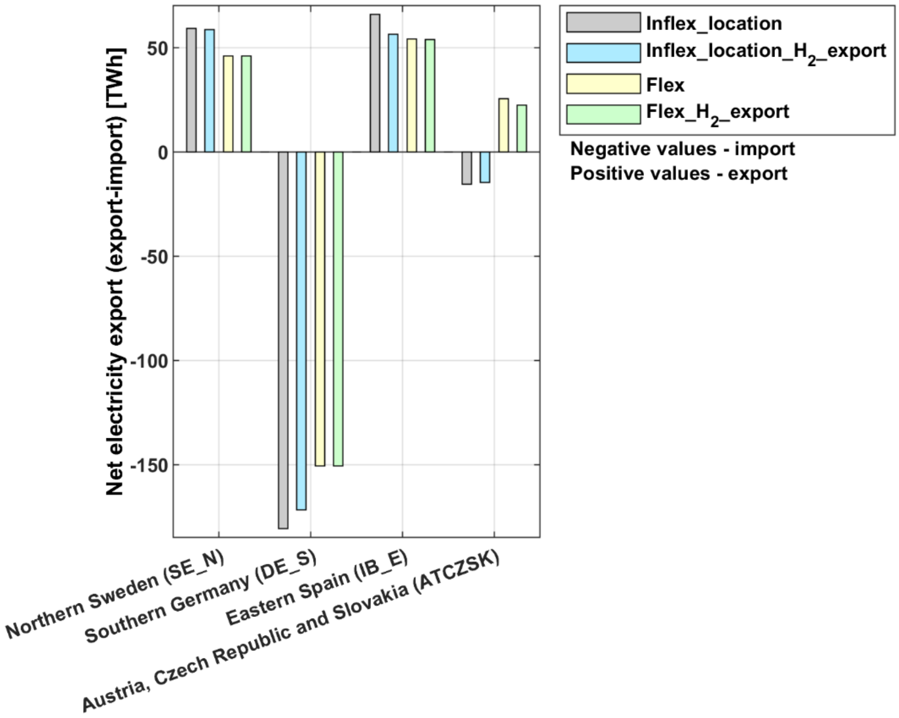
4.4.1 Hydrogen export and its impacts

The effects of a hydrogen pipeline network, i.e., trade in hydrogen, on electrified industries, in comparison with exclusively grid-connected industries were investigated in **Paper V**.

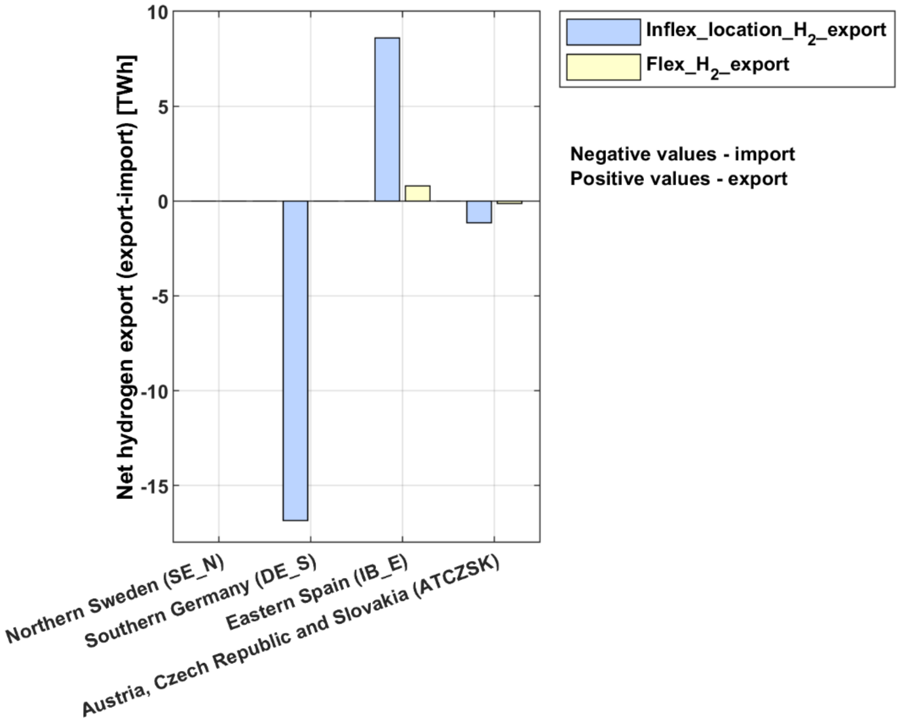
Scenario descriptions. In this section, the results from this work are presented for the example of four scenarios of *Flex*, *Inflex_Location*, *Flex_H_2_export*, and *Inflex_Location_H_2_export*. The details of the scenarios investigated in this work can be found in Appendix A, Figure A.2. The *Flex* and *Inflex_Location* scenarios do not have hydrogen export (see Section 4.2).

The *Inflex_location_H_2_export* scenario describes the case when all parts of the production chain of the electrified industries are located in the same regions as today, except for the electrolyser capacity, i.e., hydrogen trade via pipelines is allowed. The *Flex_H_2_export* scenario presents the cost-efficient geographical location of the parts of the supply chains of the electrified industries, including hydrogen production.

Figure 4.10 presents the net electricity (a) and hydrogen (b) exports, i.e., the difference between exports and imports for Northern Sweden (SE_N), Southern Germany (DE_S), Eastern Spain (IB_E), and Austria, Czech Republic and Slovakia (ATCZSK) for the investigated scenarios.



a)



b)

Figure 4.10:The net exports of electricity (a) and the nets export of hydrogen (b) for Northern Sweden (SE_N), Southern Germany (DE_S), Eastern Spain (IB_E), and Austria, Czech Republic and Slovakia (ATCZSK) for the investigated scenarios. Note the different scale of the *y*-axis in Figure 4.10b. [Source: Figure 4 in **Paper V**].

The large-scale electrification of industries leads to high demands for electricity and hydrogen in the industry-intense regions such as DE_S and ATCZSK. In these regions for the *Inflex_location_*H_2*_export* scenario, the electrolyser capacity moves to the regions that have access to low-cost electricity (Figure 4.9), i.e., electricity imports (Figure 4.10a) decrease and hydrogen imports (Figure 4.10b) increase, as compared with the *Inflex_location* scenario. When there is flexibility in location of the industries, as applied in the *Flex* and *Flex_*H_2*_export* scenarios, electricity imports decrease further in the industry-intense regions, such as DE_S. In the ATCZSK region in the *Flex_location* scenario, the direct electricity demand from industry decreases by 50% and the indirect electricity demand drops by 90%, as compared with the *Inflex_location* scenario. The units with high operational flexibility, such as the electrolyser and the steel and ammonia production units, move from the ATCZSK region to the regions with low-cost electricity. However, while electricity consumption in the ATCZSK decreases dramatically, electricity production is only slightly reduced and ATCZSK starts to export electricity. There are two reasons why the ATCZSK region starts to export electricity instead of utilising it on-site for commodities production. The first reason is to reduce investments in transmission lines. The ROBGGR region is the largest exporter of electricity to ATCZSK in the *Inflex_location* scenario. The model moves hydrogen and ammonia production to the ROBGGR region to avoid investments in the transmission line[2] (the grid capacity of ROBGGR decreases from 9.3 GW in the *Inflex_location* scenario to 7.6 GW in the *Flex* scenario) and to utilise electricity within the region. The second reason is to decrease investments in nuclear power. The DE_S and ALP_W regions border ATCZSK and these regions reduce the electricity capacity from nuclear power by 17% and 30%, respectively, whereas they increase the import of electricity from the ATCZSK region by 24% and 50%, respectively, in the scenario with the optimised location in comparison to the present-day location scenario.

As for the regions with access to low-cost electricity, as is the case for SE_N and IB_E, electricity exports decrease, while commodities exports increase in the scenarios with optimised location of industries (*Flex* and *Flex_*H_2*_export*), as compared with the scenarios with the present-day location of industries (*Inflex_location* and *Inflex_location_*H_2*_export*). With the present-day location of industries as applied in the *Inflex_location_*H_2*_export* scenario, a hydrogen pipeline network provides a way to connect regions with access to low-cost electricity to industry-intense regions, and this can reduce hydrogen production costs compared to a situation in which all of the hydrogen demand has to be provided on-site (*Inflex_location* scenario).

Key message. In the scenario with present-day location of the industry, hydrogen export via a pipeline network allows the movement of the electrolyser capacity from industry-intensive regions to regions with access to low-cost electricity, which reduces the hydrogen production costs by 3% compared to the scenario without hydrogen trade. With optimal geographical location of the industries, hydrogen production is within the same region as the hydrogen-consuming units, which means that a hydrogen pipeline has no significant impact on the hydrogen production cost.

[2] In the model applied in this study, trade between regions is limited by the transmission capacity with the existing grid capacity as the starting point, and the possibility to invest in additional capacity. Investments in additional grid capacity are constrained by the projected capacity increases for Year 2040 provided by ENTSO-E [135].

4.4.2 Electricity cost as a determinant of the location of new industries

Based on the results from **Papers III** and **V**, the electrification of basic materials industry influences the geographical location of future industry in three ways: (i) moving production to regions without existing basic materials industries; (ii) increasing the capacity and/or production in the regions with existing industry; and (iii) separation of the parts of the existing supply chain.

Table 4.2 lists the characteristics of the electrification options for the industries investigated in this work and the impacts of these options on the location of the industries. The column labelled 'Operational flexibility' in Table 4.2 shows the minimum range of the load of the industrial units for each industry. Note that the electrolyser is not included in Table 4.2.

'Electricity intensity' represents the direct electricity input (e.g., plasma rotary kiln, EAF, electrified heat of steam cracker). 'Hydrogen intensity' refers to indirect electrification, i.e., the demands of industrial units for hydrogen and hydrogen-rich fuels and feedstocks.

The values shown for 'Raw material intensity' for each investigated industry are derived from the modelling results in **Paper V**. 'Raw material intensity' represents the share of the cost of the raw material in the total production cost of the commodity, i.e., the share of the iron ore cost in the total steel production cost, the share of the cost of limestone in the total cement production cost, and the share of the cost of the waste and plastics waste in the total plastics production cost.

The 'Intermediate product' in an electrified supply chain allows not only for the temporal distribution of the electricity consumption of the process by means of storage, i.e., hydrogen, and HBI storage (see Sections 2.3 and 2.4), but also the geographical separation of the parts of the supply chain.

The 'Existing infrastructure' column presents equipment that can be used in the new electrified process. For the cement and ammonia industries, investments in new production units are required. For the steel industry, existing EAFs can be used in the electrified steel production process, although the opportunity to use existing EAFs is not investigated in this work. The locations and capacities of the existing chemical factories are used in this work.

Based on the results presented in **Papers III** and **V**, the impact of the electrification on the location of industrial sites depends on the industry's characteristics. From the modelling results presented in **Paper V**, it is clear that an industry that has a high hydrogen intensity, for which investments in new infrastructure could either be done at an existing site at a lower cost or in a new location at a higher investment cost, i.e., the ammonia industry, moves to locations that have access to low-cost electricity. This means that a low electricity cost compensates for a higher investment cost. Since hydrogen production via electrolysis is not an established part of the existing industrial supply chain, placing it at a location different from that of the rest of the process is rational if the cost of electricity to produce hydrogen is lower than the hydrogen transportation cost.

The current work neglects the capacities of the ports and the storage time for commodities, instead assuming that the ports are always available to receive and store commodities. Capacity constraints, collection and distribution systems in the port, and specific maritime safety are relevant issues when analysing access to port services and warrant further investigation. It is obvious that the existing infrastructure prevents industries from moving to new locations.

However, it can also limit the expansion of capacity for the existing industries, despite good conditions for VRE and low-cost access to raw materials in the regions with existing industries. Low-to-medium operational flexibility, as for the cement and plastics industries, reduces the incentive to move these industries once electrified to regions with good conditions for wind and solar power, since the industrial units cannot absorb electricity during low-cost events. Based on the modelling results, it is observed that commodities production increases in the regions with a low average electricity price. The impact of raw material intensity on the location of industry is not straightforward. Historically, production was located close to raw materials, so as to minimise transportation costs, as in the case of the cement industry. However, new parts of the supply chain step, such as those for the steel industry (HBI production step; for details, see Section 2.3) can lead to a situation in which the region instead of exporting raw materials exports intermediate products, which can change the existing trade flows.

Table 4.2: Specifications and impacts of assumed electrified options for the energy-intensive basic materials industries.

Industry – electrified option	**Operational flexibility, % (Units name: min. range)**	**Characteristics of the electrified options used in this work for the energy-intensive basic materials industries**					**Impact of the electrification on location**
		Electricity intensity, MWh/t commodity	H_2 intensity, MWh_{el}/t commodity	Raw material (not H_2) intensity[f], %	Intermediate product	Existing infrastructure that can be re-used	
Steel – H-DR process[a]	DR Shaft furnace: 30 EAF	1	2.2	50	HBI	-	Increases production in the regions with existing industry / Separation of the parts of the supply chain
Cement – plasma[b]	Plasma kiln: 50	1.2–1.3	-	8	-	-	Increases production in the regions with existing industry
Ammonia – Power-to-ammonia[c]	HB: 20 ASU: 60	1	8.6	-	-	-	Moves the entire supply chain to the new location
Plastics – Gasification via electrified steam cracker[d]	Steam cracker: 50 Steam reformer: 50 Synthesis: 25 MTO: 50	7.5	0–6.7[e]	20	Methanol	Chemical factories	Separation of the parts of the supply chain

HB, Haber-Bosch process; ASU, air separation unit; DR, direct reduction; EAF, electric arc furnace; MTO, methanol-to-olefins unit

[a] The values for the operational range of steel production units are taken from [94,138]. The electricity demand (direct electricity and electricity required to produce hydrogen) of steel production units is obtained from [55,56,58,59].

[b] The values for the plasma kiln are taken from [73].

[c] The values for the operational range of ammonia production units are taken from [103]. The electricity demand (direct electricity and electricity required to produce hydrogen) of ammonia production units is obtained from [87,149].

[d] The values for plastics production units are taken from [79].

[e] The total electricity consumption of the plastics production process varies in the range of 7.5–14.2 MWh per tonne of plastics depending on CO_2 utilisation, i.e., the CO_2 emissions that arise from the process can be captured and converted to methanol through a synthesis process or CO_2 can be captured and stored.

[f] The values for shares of the raw material cost in the commodity production cost, as obtained from **Paper V**.

It should be mentioned that, in reality, the movement of electrified production to regions without existing industries is unlikely to happen. Changing the location of already existing industries is complicated, given that they have to consider not only the various location factors, but also cooperation with other industries, existing customer or client bases, the business climate, the educational system, and the labour market. The model applied in **Papers III** and **V** is limited by the representation of only the techno-economic factors that impact the geographical location of the electrified industry. Thus, we cannot estimate the full impacts of the electrification. However, modelling provides useful insights into the impacts of the electricity price as a factor that influences the location of electrified industries.

Key message. The modelling results show that when considering only techno-economic factors for industries with high operational flexibility and high hydrogen intensity (ammonia industry), the main parameter that affects their geographical location is the availability of low-cost electricity.

The spatial distribution of industries for which feedstock and electricity costs constitute the largest shares of the production cost (steel industry) is affected by low-cost access to feedstock and the availability of low-cost electricity. Thus, the difference in the cost of electricity between regions is sufficiently large for industries with flexible electricity consumption in time to compensate for the increase in the cost of transportation for these industries.

The modelling results of this work indicate that an industry with low operational flexibility (cement industry) is limited in terms of its ability to take advantage of low-cost electricity from wind and solar power and, thus, investments in new infrastructure are made in existing sites. The supply chains of the industries for which existing industrial units can be used in the new electrified process and with high hydrogen intensity are separated. This means that the hydrogen production step moves to a new location with availability of low-cost electricity generation, rather than being located at the same site as the existing industrial units.

4.5 Impact of CO_2 utilisation flexibility (Paper IV)

This section describes how the electricity system impacts the optimised CO_2 stream utilisation in the plastics production process. As mentioned in Section 2.3, when waste is used to produce plastics, the CO_2 emissions that arise from the waste gasification process can be captured to produce olefins via a synthesis process (CCU mode) or be stored (CCS mode). Using the CO_2 emissions to produce olefins requires hydrogen and thus increases electricity consumption.

Scenario descriptions. To investigate the influence of the electricity system on the CO_2 utilisation for plastics producers two scenarios were studied *Flex* and *Inflex_time*. As described in Section 4.2, the *Flex* scenario includes all flexibility options investigated in this work (Section 2.4). In the *Inflex_time* scenario, all plastics production capacities (the steam cracker, steam reformer, synthesis, electrolyser and methanol-to-olefins process) operate continuously and investing in commodities and hydrogen storage is not allowed; capacity utilisation is close to 100%.

It is found that the amount of stored CO_2 (CCS mode) is lowest in the *Flex* scenario and highest in the *Inflex_time*, among the investigated scenarios (see Figure 4.3, Section 4.2). The amount of CO_2 emissions captured from the process is four-fold greater in the *Inflex_time* scenario than in the *Flex* scenario. The reason for this is that flexibility in CO_2 utilisation (see Section 2.4) compensates for the limitation of the flexibility in time in the *Inflex_time* scenario, i.e., when the electricity price is high, the CO_2 stream from the cracker is captured and stored to avoid electricity consumption.

Figure 4.11 and Figure 4.12 present the marginal electricity price profiles and CO_2 utilisation modes for the steam cracker based on plastic waste for southern Germany (DE_S), and for Norway (NO_T) for the scenario with full flexibility (flexibility in regard to time and location, and flexibility of CO_2 utilisation) of the plastics production process, i.e., *Flex* (a) and for the scenario when the electricity consumption of the plastics production units cannot be shifted in time, i.e., *Inflex_time* (b) scenarios (*cf*. Section 2.4) for two weeks in September.

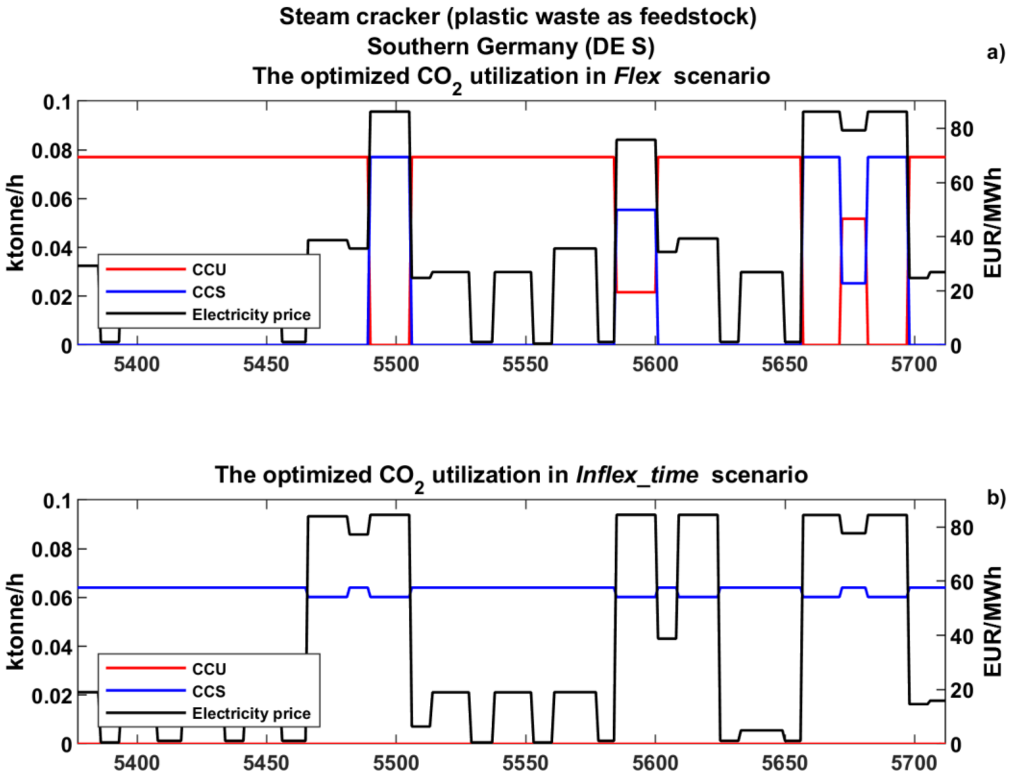


Figure 4.11: Electricity price profiles (€/MWh) and CO_2 utilisation levels (ktonne) (i.e., CCS and CCU) for steam crackers based on plastic waste for southern Germany (DE_S) for the *Flex* (a) and *Inflex_time* (b) scenarios for two weeks in September. CCS, carbon capture and storage; CCU, carbon capture and utilisation. [Source: Figure 8 in **Paper IV**].

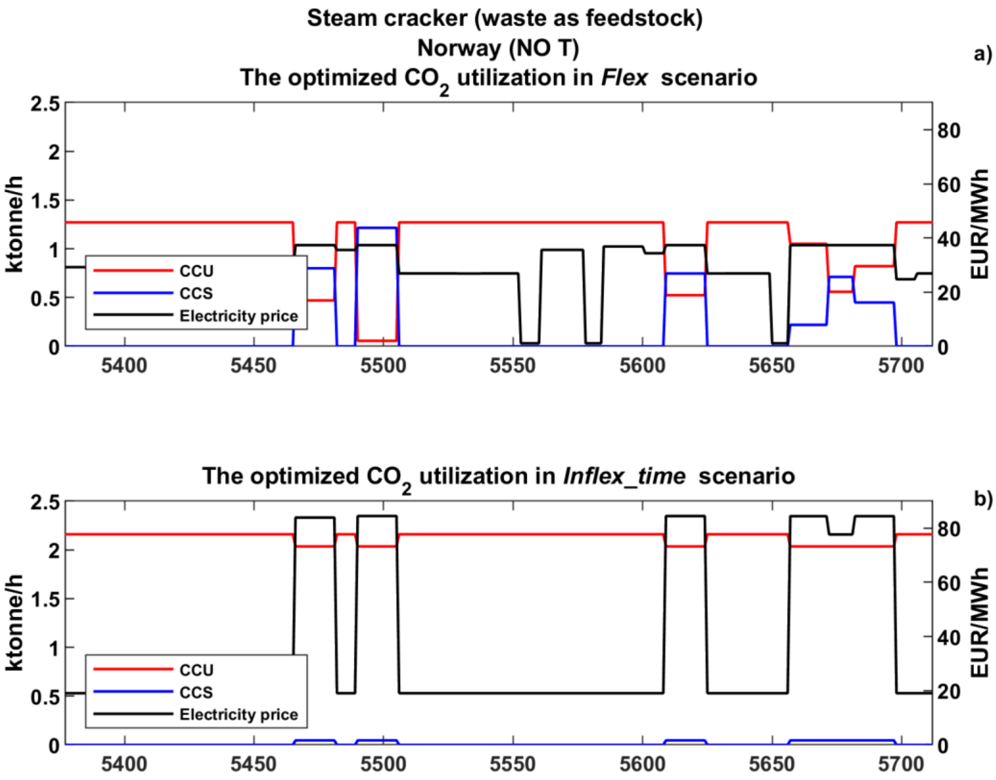


Figure 4.12: Electricity price profiles (€/MWh) and CO_2 utilisation levels (ktonne) (i.e., CCS and CCU) for steam crackers based on waste for Norway (NO_T) for the *Flex* (a) and *Inflex_time* (b) scenarios for two weeks in September. CCS, carbon capture and storage; CCU, carbon capture and utilisation. [Source: Figure 9 in **Paper IV**].

Figure 4.11a and Figure 4.12a show that for the *Flex* scenario, CO_2 utilisation modes (CCS and CCU) follow the variations in the electricity price in both countries. In southern Germany, CO_2 released from the processing feedstock is stored and captured during high electricity prices close to or above 80 €/MWh (Figure 4.11a, Hours 5,500, 5,650–5,700). When the electricity price varies in the range of 5–40 €/MWh, CO_2 emissions released from the processing feedstock are sent for synthesis to produce methanol. As for Norway, the CO_2 emissions are captured and stored when the electricity price is close to or above 40 €/MWh (Figure 4.12a, Hours 5,500 and 5,650).

For the *Inflex_time* scenario, when flexibility in time is limited and plastics production units cannot follow variations in the electricity prices, the CO_2 utilisation behaviour is different in Norway than in southern Germany (Figure 4.11b and Figure 4.12b). The strong availability of low-cost electricity based on hydro and wind power in Norway incentivizes investments in large steam cracker capacity based on waste in this region when there is flexibility as to location. The allocation of the large steam cracker capacity in the *Inflex_time* scenario leads to an increase in the amplitude of the electricity price fluctuation, which is in the range of 20–80 €/MWh, as compared to 5–40 €/MWh for the *Flex* scenario. However, CO_2 emissions released from process feedstock are utilised to produce plastic. The steam cracker plant starts to capture and store CO_2 emissions only when the electricity price reaches more than 80 €/MWh (Figure 4.12b).

As for southern Germany, in the *Inflex_time* scenario, CO_2 emissions are never processed into methanol, although the steam cracker varies the feedstock input to reduce electricity consumption and, for that reason, the CO_2 emissions flow that is captured decreases during periods with electricity prices higher than 80 €/MWh (Figure 4.11b).

Plastic production with flexibility in time renders 100% carbon recovery cost-effective, whereas inflexible operation of the plastics production process requires development and scaling-up of carbon capture and storage facilities.

Key message. Based on the modelling results from **Papers IV** it was found that the ability to switch between the two above mentioned CO_2 utilisation modes (i.e., CCU and CCS) would allow industries which have CO_2 emissions from production processes (i.e., plastic production), to avoid the consumption of electricity during high-cost events.

4.6 Combined impact of energy-intensive basic materials industries (Paper V)

This section lists the results from the investigation of how the potential future electricity demands from industries that have different types and levels of flexibility (see Section 2.4) influence the cost of hydrogen. This is achieved using the ENODE model (**Paper V**).

Scenario descriptions. The details of the scenarios studied in this sub-section can be found in Appendix A, Figure A.2.

The scenarios in this sub-section vary in the type of industry that is electrified (ammonia, cement, steel, plastics) and the flexibility options that can be applied (flexibility in time and location and flexibility in CO_2 utilisation, the square under the parameter name indicates "yes" if included). The electrified ammonia industry is used as the reference industry to investigate how the electrification of industries impacts hydrogen production costs, since ammonia production is the most-hydrogen-intensive industry and has the highest operational flexibility among all the industries investigated in this study. The names of the scenarios with all flexibility options start with *Flex*; with limited flexibility in time - *Inflex_time*; with limited flexibility in location - *Inflex_location*; and with both limited flexibility in time and location – *Inflex_time_location*.

Figure 4.13 shows the break-down of the hydrogen production cost per MWh for the scenarios in which: only the ammonia industry is electrified; the ammonia and steel industries are electrified; and all the investigated industries (i.e., ammonia, cement, steel, and plastics) are electrified. The model results for the scenarios with electrified ammonia and cement industries, as well as with electrified ammonia and plastics industries are given in Figure A.3, Appendix A. The cost is divided into the annualised investment cost, the fixed operational and maintenance costs (O&M) costs, the cost of electricity, and the transportation costs.

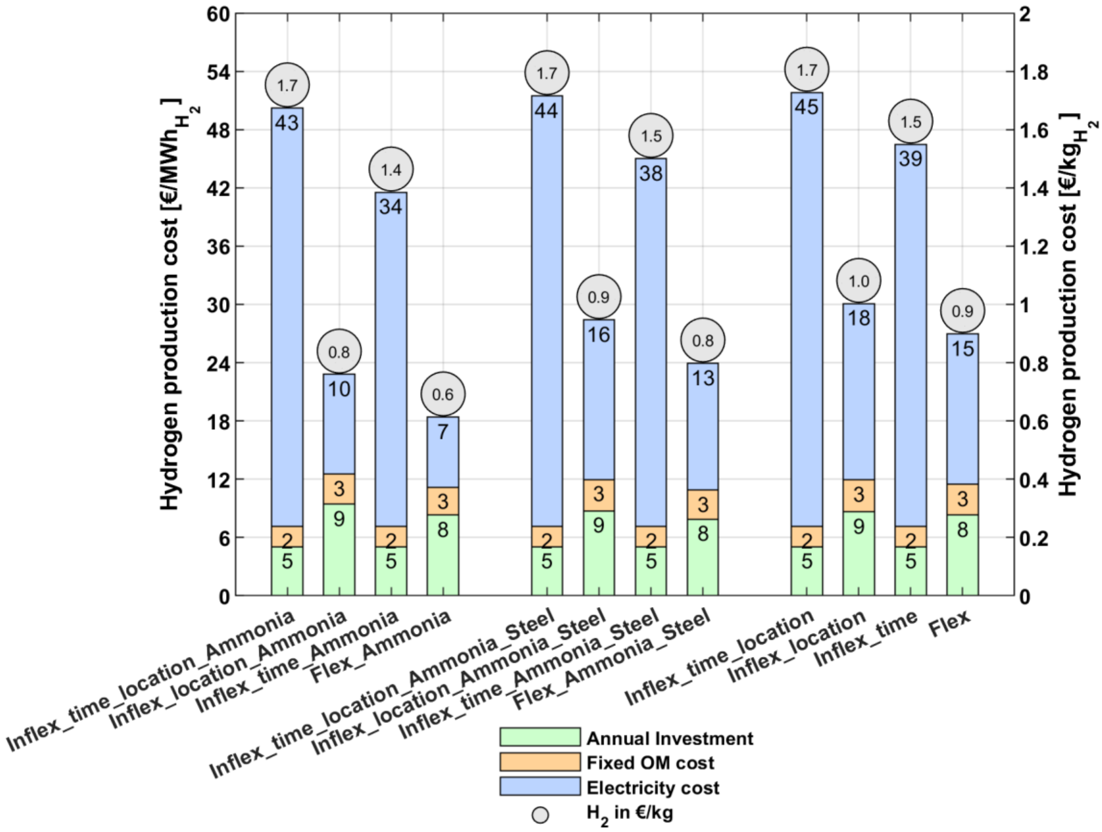


Figure 4.13: The hydrogen production cost obtained from the modelling for the scenarios in which only the ammonia industry is electrified, scenarios in which the ammonia and steel industries are electrified, and scenarios in which all industries are electrified (i.e., ammonia, cement, steel, and plastics) are electrified. The scenarios with all flexibility options begin with *Flex*. Scenarios with limited flexibility in time or location are denoted by *Inflex_time* or *Inflex_location*, respectively. Scenarios with limited flexibility in both time and location are titled with *Inflex_time_location*. Hydrogen production cost includes the annualized investment cost, the fixed O&M costs, the electricity cost and hydrogen transportation costs for the investigated scenarios. Please note that investments cost for electrolyser of 550 €/kW_{el} are used for this study.

The modelled costs given in Figure 4.13 yield a hydrogen production cost that ranges from 18 to 44 €/MWh_{h2} (corresponding to 0.6–1.7 €/kg of hydrogen) for the investigated scenarios. The relatively low hydrogen cost obtained in this work is due to the ability of the electrolyser to follow electricity price variations (see Section 2.4 for details). The range of hydrogen costs projected by the IEA is 1.1–4.0 €/kg of hydrogen. The electricity cost constitutes 55% of the total hydrogen production cost obtained from the IEA, assuming that in regions with good access to renewable energy, the cost of electricity (mainly from solar power) for hydrogen production is 14 €/MWh and that the electrolyser operates for 2,600 full-load hours. According to the IEA projections, by Year 2030 the electrolyser investments cost will have decreased to 300–500 €/kW compared to the current levels (1,400–1,770 €/kW), due to the scaling up of electrolyser capacity [150]. As a consequence of the falling costs for electrolysers, BloombergNEF [151] projects that renewable hydrogen could be produced for 0.6–1.4 €/kg in most parts of the world before Year 2050. The current work and other projections [121,122] suggest that two important factors are crucial to decreasing the cost of producing hydrogen: the flexible consumption by the electrolysers of the electricity supplied from VRE; and the scaling up of the electrolyser capacity.

The modelling results show that in the future European electricity system, the lowest cost for hydrogen production arises from production with full flexibility, i.e., flexibility in both time and location, and flexibility of CO_2 utilisation. The limitation of the flexibility in time for the industrial units has a stronger impact on the hydrogen production cost compared with the scenarios in which the flexibility in location is limited. For scenarios with limited flexibility in time, the hydrogen cost increases by 100%, and for scenarios with limited flexibility in location the hydrogen cost increases by 20%, as compared with the scenarios in which all flexibility options are available.

The hydrogen production cost is affected by not only industrial flexibility options but also by commodity demands. The low-medium operational flexibility of plasma kilns makes it challenging to follow electricity price variations. Nonetheless, the electrification of both the ammonia and cement industries, when at least one flexibility option is available, leads to a 1%–4% increase in the hydrogen cost compared to electrifying only the ammonia industry. In contrast, electrification of the ammonia and steel industries results in an 8%–23% increase in the hydrogen cost, and electrification of ammonia and plastics production processes leads to a 2%–17% increase in the hydrogen cost. The lower increase in hydrogen cost when the ammonia and cement industries are electrified, as compared to the scenario where the ammonia industry is electrified along with steel and plastics production, is attributed to the low total electricity demand from cement production driven by the demand for cement. In other words, the lower hydrogen cost increase can be attributed to the fact that the cement industry requires less electricity in total (under the given assumptions regarding the cement demand) than the steel and plastics industries.

Among the scenarios in which only two industries are electrified, the highest cost for hydrogen production arises when the ammonia and steel industries are electrified. The high electricity demand driven by the steel demand reduces access to sites with good conditions for VRE. Thus, the number of high electricity price events increases, and this diminishes the value of the operational flexibility of the steel production units.

When electrifying the plastics and ammonia industries, flexibility in CO_2 utilisation compensates for the limited flexibility in time. Thus, the ability to switch between CO_2 utilisation modes (i.e., between CCU and CCS) allows the industrial units to avoid the consumption of electricity during high-cost events, which also implies increased costs for feedstock and CCS.

Figure 4.14 presents the location and size of the DR shaft furnace capacity (in ktonnes) for two scenarios (*Flex* and *Flex_Ammonia_Steel*) in which the industrial units have full flexibility. In the *Flex* scenario, all the investigated industries are electrified, while in the *Flex_Ammonia_Steel* scenario, only the ammonia and steel industries are electrified.

Figure 4.14 shows that electrification of only the ammonia and steel industries, as applied in the *Flex_Ammonia_Steel* scenario, leads to the clustering of the DR shaft furnace capacity around countries that have good conditions for VRE and low-cost access to iron ore, such as FR_N. The electrification of the ammonia, cement, steel, and plastics industries (*Flex* scenario) results in investments, and investments in DR shaft furnace capacity increase in the regions that have existing steel production in UK_S, SE_N and FI_T, as compared with the *Flex_Ammonia_Steel* scenario.

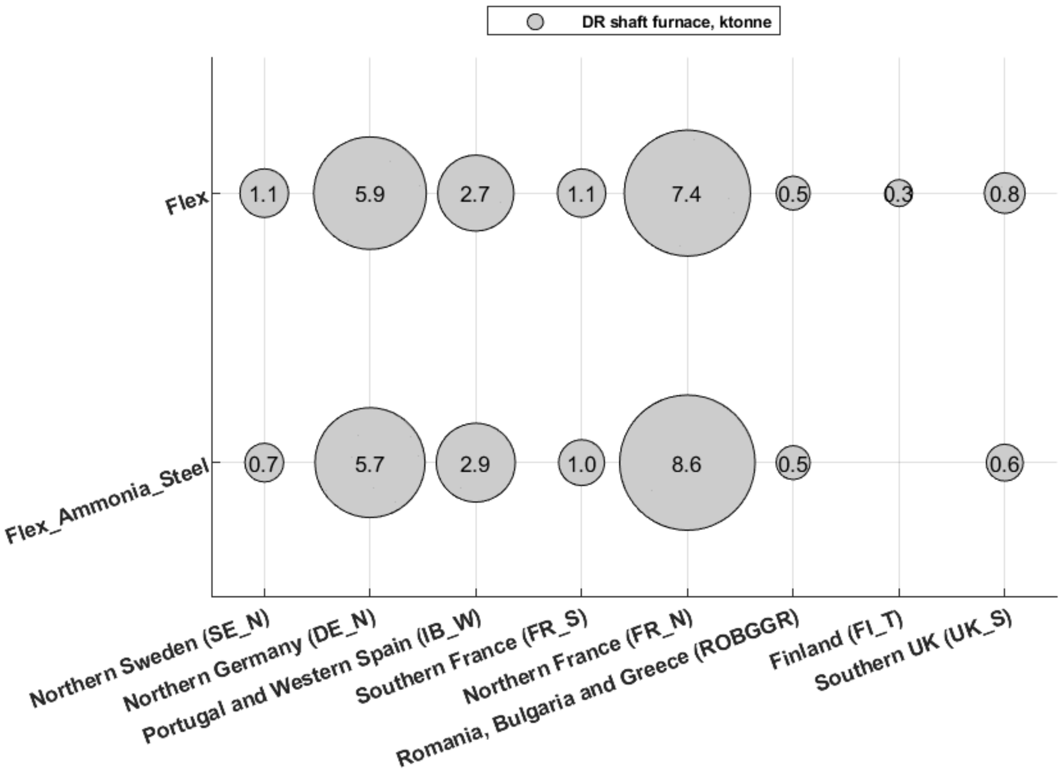


Figure 4.14: The modelling results for the regional allocations of the steel production capacities in terms of the DR shaft furnace (in ktonnes) for the *Flex_Ammonia_Steel* and *Flex* scenarios.

Key message. The combination of all the industrial flexibility options included in this work (Section 2.4) gives the lowest hydrogen production cost for the investigated scenarios.

Among the flexibility options, flexibility in time, i.e., the ability to follow electricity price variations, gives the greatest reduction in hydrogen production costs, as compared with the scenarios without industrial flexibility options. With flexibility in location, it is possible to utilise solar power sites and remote areas for wind power generation sites to satisfy the electricity demand from industry.

The difference in hydrogen production cost between scenarios with different combinations of flexibility options decreases in line with the size of the demand for hydrogen. The decreased value of industrial flexibility when the electricity demand from industry grows is due to the reduced access to sites with good conditions for VRE and the fact that some regions invest in nuclear power, which benefits less from the industrial flexibility options. Still, even with the electrification of all ammonia, cement, steel, and plastics production processes in the EU, industrial flexibility options retain value.

5 Discussion

Electricity system transition. An important challenge identified in this work is the magnitude of new electricity generation required to meet future demands for electricity. Meeting this demand at the lowest cost entails extensive expansion of wind and solar power.

The results of the model applied in **Paper V** indicate that the expansion rate of offshore wind in the EU (current capacity of 22GW) should be 8 GW annually to reach the model result of 300 GW in Year 2050. As for onshore wind capacity, the model results indicate a total demand for wind capacity of 434 GW in the EU for Year 2050. This means that to reach this level, the average expansion rate should be 8.5 GW per year, which is lower than the average onshore wind expansion rate (9 GW per year) between 2005 and 2020. For Germany, the country with the largest installed PV capacity (49 GW) in the EU, the average expansion rate of PV for the period of 2020–2050 should be 3 GW per year in all the investigated scenarios, to arrive at a capacity of 153 GW in Year 2050. This capacity increase is only somewhat higher than in recent years, when the average expansion rate of PV was 2.5 GW per year (between 2005 and 2020) [152]. The highest increase in nuclear power capacity (143 GW) is obtained for the scenarios without industrial flexibility options. In the EU, for the period of 2000–2019, nuclear power capacity declined by 12% (from 135 GW to 119 GW). The deployment rate of nuclear power capacity should be 0.8 GW per year to achieve an additional capacity increase of 143 GW in Year 2050.

Hydrogen supply. This work emphasizes that electrolysers are critical components of the industrial transition towards electrification. Based on the results of this work, the required electrolyser capacity for the region investigated (the EU) when the basic materials industry is electrified, considering industrial flexibility options, equals 114 GW. Moreover, 53 GW of electrolyser capacity are needed if the industry does not consider flexibility options and if emissions from the plastic production process are captured and stored. These electrolysers would require 460–740 TWh of electricity, where the range reflects the extent to which the CO_2 released from the plastics production is captured and stored. The required electricity demand obtained from the model for the electrolyser represents around 25% (2,100 TWh) of the current electricity demand of the EU.

Rapid scaling-up of the electrolyser capacity is essential to meet the mid- to long-term hydrogen demands. Starting at 135 MW in the EU in Year 2021 [153], the electrolyser capacity needs to have a deployment rate of 4 GW per Year from 2021 to 2050 to meet the hydrogen demands of the electrified basic material industries obtained in this work (i.e., 114 GW in Year 2050). Electrolyser manufacturers in the EU have signed a declaration of commitment to build an electrolyser capacity of 17.5 GW_{h2} in Europe by 2025, which is in line with what is required to realise the outcomes obtained in this work [154].

Odenweller and co-workers have assessed the potential deployment of electrolyser capacity by combining an S-shaped logistic technology diffusion model with a probabilistic parameterisation based on trends in wind and solar power expansion rates [155]. They have assumed that the short-term target for hydrogen supply in the EU is 100 GW in Year 2030, based on the REPowerEU Plan, and that the long-term target is set at 500 GW by Year 2050, as mentioned in the EU Hydrogen Strategy [148]. The EU Hydrogen Strategy takes into account the demand for hydrogen in sectors other than industry, such as transport (aviation and shipping) and buildings, thereby yielding an electrolyser capacity that is five-times higher than that in the current study. Odenweller and colleagues have found that if the electrolyser capacity grows at a similar rate to wind and solar power, the hydrogen supply will probably (≥75%) remain scarce until Year 2030 in the EU. However, a break-through is expected with respect to the largest annual electrolyser capacity additions by Year 2040 in the EU. The lack of sufficient electrolyser capacity delays both the end-user (i.e., industry) transformation and the required infrastructure developments (i.e., network pipelines). Odenweller and colleagues have concluded that the achievement of sufficiently high growth rates for electrolyser capacity will require rapid investments fostered by policy makers and industry.

Schlund et al. [156] conducted a stakeholder analysis of a hydrogen market ramp-up in Germany. They identified a total of 49 stakeholder groups, and the relationships between these groups were analysed using Social Network Analysis (SNA) and Qualitative Content Analysis (QCA). The analysis conducted by Schlund et al. showed that the scaling-up of the hydrogen market will alter stakeholders' roles along the hydrogen value chain. The electricity utilities are expected to become the central players regarding the production of hydrogen based on renewable energy, thereby partially replacing the chemical industry and industrial gas companies as producers of hydrogen (currently from steam methane reforming). The risks that are anticipated to appear along the hydrogen value chain during the market ramp-up include technical challenges, uncertainties regarding costs, and acceptance issues.

5.1 Model limitations

This section outlines the limitations and highlights areas for improvement of the models used in this work.

Greenfield model. A greenfield approach was applied throughout this work, which means that the constraints and limitations imposed by the existing electricity system and industrial infrastructure are not considered, with some exceptions. The model considers the current transmission lines, hydropower, and nuclear power in Finland. In addition, placing industry in regions that did not previously accommodate that type of industry is associated with a cost that represents the deployment of the new sites. The motivation for a greenfield approach is that almost all the electricity generation technologies and industrial units that are currently in use will, in any case, require replacement within the period of time up to the investigated Year 2050.

Using this greenfield modelling methodology, the results indicate the cost-optimal composition of the electricity system, considering the conditions of the year investigated, rather than the anticipated investments for that year. Thus, the greenfield perspective does not provide a framework for analysing the stages of development, such as how the electricity system can transition gradually to achieve high renewable energy shares or how the industry can move towards zero-emissions production in a step-by-step manner. The absence of any representation of a transition pathway for the system from the present to Year 2050 makes the greenfield model computationally faster and enables multiple sensitivity analyses, which are crucial for this study given the high degree of uncertainty related to the parameter-related assumptions made for the future industry. Thus, the results should not be interpreted as a forecast but rather as a benchmark for an optimised future system.

Perfect foresight. In this work, variables are calculated with perfect foresight for a single reference year. Perfect foresight is an artefact of the linear-programming method. It means that the decisions in each time-step of the model are made with knowledge of future outcomes and the consequences of earlier decisions [157]. This means that the model does not account for unexpected weather events that impact the outputs of the modelling, such as investments in storage capacity. In addition, one historical year is applied to represent the weather conditions for the investigated year. The inclusion of the inter-annual wind and solar variations results in larger investments in the capacity for long-term storage systems, as compared to accounting only for single-year variations [158]. This is because wind power exhibits larger inter-annual variations than solar power [159,160].

Technology cost and availability. The costs and availability levels of technologies are important parameters for designing a cost-optimal system. As shown in Section 2.2, the Technology Readiness Level (TRL) of the technologies assumed for the electrified production processes of basic materials industries vary. Technologies such as EAFs for steel production are commercially available and are already in use. However, technologies such as plasma kilns for cement production are in the early stages of development and are at TRL 3 [74]. Technological learning and development are complex issues. The commercialisation of novel industrial technologies (especially those for high-temperature processes), the high capital costs of commercialised technologies, and the risk aversion of industries are factors that can increase the assumed cost of the investigated technologies. Nevertheless, the dynamic interplay between electrified industries and the electricity system addressed in this work can to a large degree be useful for different stakeholders, even if the real-life development proceeds faster or slower than is anticipated in this work (i.e., all the technologies for the electrified industries are available by Year 2050). The purpose of this work was not to create a perfect picture of the future, but rather to assess the opportunities to utilise industrial flexibility options in a- future electricity system with a high share of VRE.

5.2 Considerations for future research

There are many other aspects of the electrification of industry and its implications for the electricity system that need to be studied further. This chapter discuss some of these aspects, most of which are related to the work performed for this thesis.

Development of the industrial electrification over time. To further improve our understanding of the implications of industrial electrification, it is crucial to consider parameters such as the existing industrial capacity, its age structure, and the TRLs of the abatement measures (Section 2.4). As demonstrated in Section 4.6, the effects of electrification, such as the cost of hydrogen production for the industry, may vary depending on whether one or multiple sectors are electrified simultaneously.

Investment decisions regarding industrial units, such as those in over-capacity and storage to take advantage of electricity price variations, which are made by the "first" industry that electrifies its production could impact the investment decisions of subsequent industries (see Section 4.6). Furthermore, the benefits of the industrial flexibility options provided by electrification might lessen as more industries electrify their production processes. Thus, further analysis is needed to understand the different stages of the industrial transition toward electrification.

Multi-annual time-frame. Ruhnau and Qvist [158] have applied a cost-minimising electricity system optimisation model of Germany to investigate the hydrogen storage capacity required for a 100% renewable electricity system. They have compared scenarios with a multi-year time series (35 years) and single-year data for renewable generation and load. They have shown that the storage volume in a 100% RES system can be doubled if the variability across a 35-year period is considered, i.e., accounting for the maximum energy deficit. However, as opposed to the work presented in this thesis, they do not consider multiple regions with the possibility for the import/export of electricity and other commodities between the regions, and they only consider hydrogen and batteries as flexibility options. Yet, it is still relevant for future work to investigate the impacts of the inter-annual variability of renewable energy on the investments in and operation of industrial units. A reasonable assumption is that the very seldom occurrence of long periods of no wind power can be handled through means other than hydrogen storage, such as biogas-powered gas turbines (which may require a capacity market for additional biofuel storage). Future research could provide insights into what options are available for handling such rare events with respect to the financial risks and the security of electricity supply for the system.

Social and environmental aspects of the industrial electrification. While the focus of this study is primarily on the techno-economic aspects of industrial electrification, it is crucial to consider also the other dimensions of industry electrification. The electrification of industrial processes can lead to significant changes with respect to the jobs and skills required by the industry. Thus, the workforce would need to be retrained or require new education, which could create new employment opportunities, but might also cause disruption to current employment patterns. The electrification of industries also depends on social acceptance of the technology and the transition process. It is important to engage with stakeholders, i.e., community members, workers, and industry representatives, to ensure that their concerns and perspectives are considered.

The magnitude of new electricity generation based on VRE also implies changes in the raw material requirements. The EU is dependent upon imports for many of the critical raw materials (CRMs) used in wind turbines, solar photovoltaic (PV) units, and batteries. There will be increased competition for critical materials, such as borates, gallium, indium, cobalt, and for niobium, among the different sectors involved in the production of renewable energy, electric vehicles, aerospace components, digital products, chemicals, and petrochemicals [161]. Including the social and environmental aspects of the industrial electrification in energy systems models in addition to those included in this work can provide a more holistic view of the impacts of industrial electrification. Thus, research efforts could focus on developing a framework that maps, assesses, and quantifies the social and environmental aspects of industrial electrification. In addition, energy systems studies might target the incorporation of these aspects of industrial electrification into the modelling.

Trutnevyte et al. [162] have defined three strategies for linking models and social aspects: bridging, iterating, and merging. The bridging strategy is based on discussing and exchanging information between modellers and social scientists, carried out in parallel with the research. The iterating concept is a “story and simulation” approach, where scenarios are translated into quantitative input assumptions used by the models, and the outputs may be used for revisiting the narratives. The merging strategy implies modelling the societal factors (i.e., representation of the social aspects as variables), leading to structural modifications of existing models or the creation of completely new models. The common approach adopted for including social aspects in the energy systems model is to include social factors as constraints within the model (i.e., the iterating strategy). Incorporating public acceptance of renewable energy deployment strategies into energy systems models has become a particularly recent focus [163]. In this study, the potential levels of employment offered by wind power and PV are limited by the amount of space that is available, which is calculated by identifying suitable land areas and deducting unsuitable land areas from the total available area of the investigated regions, using the tool of Mattsson et al. [164]. In addition, the space available is assumed to be limited to 8%, 33%, and 5% of the land area suitable for onshore wind, offshore wind, and solar power, respectively. One of the approaches to incorporating environmental factors into the energy systems model is the integration of a module that considers the raw material requirements for implementing a renewable energy infrastructure and the constraints on the availability of these materials. The introduction of this modelling module can provide information on the demand for raw materials and allows the identification of potential supply issues.

Expansion of the geographical scope. The basic material industries are linked to the global economy. Different countries play different roles in the supply pathways for the value chains, forming a complex, global trade network. A study that analyses the electrification of the industry on the global level would be of interest. Such a study would explain the potential changes to global commodity trade flows and the geographical allocations of the electricity demand and investments that are needed to meet these challenges. Currently, there is a tendency towards so-called “re-shoring” of some production to Europe and North America. The term “re-shoring” refers to the processes of bringing industries or more parts of the value chain “home” from foreign locations [165,166]. The main drivers of re-shoring include issues related to cost, quality, time and flexibility, access to and management of skills, knowledge or infrastructure, risks and uncertainties, and the market [167]. According to Kinkel, re-shoring occurs when trade-offs between cost advantages, market- and knowledge-seeking, and maintaining direct control are no longer perceived to be advantageous [168].

The EU policies that are planned to harmonise national regulatory regimes and promote the circular economy will make out-sourced production more costly than was previously the case, thereby creating an incentive to shorten supply chains, including measures involving re-shoring [169]. Between 2010 and 2021, more than 9,000 companies in the US repatriated foreign investments (50% from Asia), which led to the creation of more than 800,000 jobs [170]. According to the European Reshoring Monitor [171], between 2015 and 2018 there were 253 re-shoring projects, with Italy and France at the top of the ranking (mostly from China and the Far East for the manufacturing sectors). This might result in a level of repatriation equivalent to 10% of foreign production.

Electrification is not a silver bullet. It is shown in **Paper I** that substantial reductions in CO_2 emissions from industry can be achieved by applying CCS together with biomass and process electrification (e.g., H-DR steelmaking). Bio-CCS implementation offers opportunities for negative emissions across European industry [172]. Thus, a modelling study that analyses a combination of the different ways to reduce CO_2 emissions from industry would be of interest. Such a study could increase understanding regarding the regional distribution of mitigation technologies across the industry and could examine the competition between the electricity system and the industry for resources such as electricity and biomass. This chapter shows that there are many aspects of industry electrification that require further research. By continuing to study these issues, we can ensure that the electricity system and the industry are prepared to meet the challenges and opportunities presented by the electrification of industry.

6 Summary and main findings

This thesis analyses and discusses the relationship between the electrification of the energy-intensive basic materials industry and the electricity generation system, applying techno-economic energy systems models. The main contributions of the thesis to the existing research on energy systems are (i) a method to represent the industry and its electrification in the techno-economic modelling; and (ii) results indicating cost-efficient investments in over-capacity and storage for industrial units, as well as the locations of future industrial plants (including commodities trade). In the context of the research questions posed in Chapter 1, the findings and conclusions from this work can be summarized as follows.

> *i. What roles do different CO_2 abatement technologies play in reducing the emissions from industry, and when in time it is reasonable to assume that these technologies can be implemented?*

The transition to zero CO_2 emissions from energy-intensive basic materials production requires switching to new processes that use energy carriers and feedstocks with zero CO_2 emissions (e.g., electricity, hydrogen, biomass), and carbon capture and storage (CCS). These options necessitate substantial scaling up of carbon-free electricity generation, hydrogen production, material recycling, and the CO_2 capture and storage infrastructure, as well as the phasing out or conversion of existing industrial plants.

The technological assessment presented in **Paper I** suggests that it is reasonable to assume that TGRBF/CCS with biomass for primary steel production and EAFs with biomass for secondary steel production can achieve an 80% reduction in CO_2 emissions already by Year 2030. The electrification of primary steel production using hydrogen, as applied in Pathway 2, would facilitate a further reduction in CO_2 emissions from steel production plants, as compared to Pathway 1, although this would require an additional electricity demand of almost 14 TWh (around 10% of the current electricity demand in Sweden) in Year 2045. Pathway 3 proposes the increased production of HBI pellets, leading to abatement of emissions from the steel industry outside Sweden, albeit with a significant increase in electricity demand (25.6 TWh) and a need for new investments in Swedish steel production capacities.

> *ii. How does the electrification of industry influence the costs of the produced commodities, and the sizing and production levels of the electrified industrial units when considering flexibility options for the electrified industry?*

Full flexibility (flexibility with regards to time and location, and flexibility of CO_2 utilisation) of the energy-intensive basic materials industry yields: 1) the lowest cost for commodities production; 2) the highest rate of carbon recovery from the feedstock; and 3) the lowest capacity utilisation rate, i.e., there is an investment in over-capacity to achieve flexibility.

The modelling results demonstrate that with full flexibility of industry, the average capacity utilisation ratio of the electrolysers is 60%, meaning that the electrolysers restrict their production during high electricity price events. In addition, it is found that the modelled average electrolyser capacity in the EU for scenarios with full flexibility of industry is twice as high as the capacity for the scenario without industrial flexibility when electrolysers operate continuously and CO_2 emissions from the plastics production processes are captured and stored.

From the modelling, it is concluded that for electrified industry, low costs for hydrogen and electricity can be achieved by avoiding high-net-load events through operational flexibility of the industrial capacity, in conjunction with the storage of hydrogen and commodities. Moreover, flexibility in regard to time is found to have the strongest impact on the cost of commodities (ammonia, cement, steel, plastics and hydrogen) among the different flexibility options. Scenarios with time flexibility limitations exhibit the highest costs for the production of commodities among the scenarios investigated.

The results show that plastics production with flexibility in time renders 100% carbon recovery beneficial, whereas inflexible operation of the commodities production process requires the development and scaling-up of CCS facilities.

iii. Which parameters determine the spatial distribution of electrified industry that yields the lowest cost?

The modelling results show that for the ammonia industry, i.e., an industry that has high operational flexibility with a corresponding load range and high hydrogen intensity, the main parameter that affects the geographical location of the plants is the availability of low-cost electricity generation. The location of ammonia production to regions with a high availability of low-cost electricity implies increased transportation of commodities, as compared to the present-day locations of ammonia production plants. For the electrified plastics and steel industries, for which the feedstocks and electricity costs constitute the largest shares of the production cost, access to low-cost feedstocks (e.g., regions that produce or distribute feedstocks or have low costs for feedstock transportation) and availability of low-cost electricity generation determine the spatial distribution. For the steel industry, localising production to ensure access to low-cost electricity is particularly favourable if the feedstock (iron ore) can be transported at low cost to the region with low-cost electricity. For the plastics industry, locating production to regions with low-cost electricity results in an increase in CO_2 utilisation to produce plastics, i.e., a high rate of carbon recovery, and a decrease in CCS costs. The determinant of localisation for the electrified cement industry with low operational flexibility is proximity to the market (in this study, the current commodities production is used as the regional commodity demand, i.e., the market). The modelling results of this work indicate that, since the cement industry has low operational flexibility, this will limit the ability to take advantage of low-cost electricity from wind and solar power and, thus, proximity to cement markets remains the main factor influencing the location of the cement production.

For the scenarios with present-day locations of the industry, the hydrogen pipeline network provides ways to connect regions with access to low-cost electricity to industry-intensive regions and to reduce the hydrogen production cost by 3% compared to the scenario without hydrogen trade. With optimal geographical location of the industries, hydrogen production is located to the same region as the industrial units and, thus, a hydrogen pipeline has no significant impact on the hydrogen production cost.

iv. Which electricity generation technologies meet the potential future electricity and hydrogen demands from industry and how do these technologies depend on the flexibility of the demand?

The modelling shows that the electrification of energy-intensive basic materials industry in the EU increases the electricity demand by around 44% (by 1,200 TWh). The modelling shows that the future European electricity demand with the present-day location of the industrial plants is primarily met by solar, wind and nuclear power. If changes to the annual production volumes and relocation of industry are allowed, more commodities are produced in the regions with both existing industries and access to low-cost electricity, thereby increasing the electricity generation from wind and solar power. All the modelled scenarios require substantial and rapid increases in renewable electricity capacity.

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Appendix A

The overview of the products that are assumed to be in the supply chain of the basic materials industries investigated in this work is given Table A.1.

Table A.1: List of the commodities included into the basic materials industries supply chain.

Industry	Raw material/Feedstock	Intermediate products	Final commodities
Steel	Iron ore	H_2, HBI	Steel
Cement	Limestone	Clinker	Cement
Ammonia	Water, air	H_2, N_2	Ammonia
Plastics	Plastic waste, waste	H_2, methanol, olefins	Plastics

Figure A.2 gives an overview of the parameters that define the different scenarios applied in this work. Three parameters (operational flexibility, trade of commodities, and CO_2 utilisation) represent the flexibility options (flexibility in time and location and flexibility in CO_2 utilisation; *cf.* Section 2.4) and four parameters show the industries investigated (ammonia, cement, steel, and plastics). These parameters can be applied (the square under the parameter name indicates "yes") or limited (the square under the parameter name indicates "no") in the applied model (*cf.* Sub-section 3.3.3).

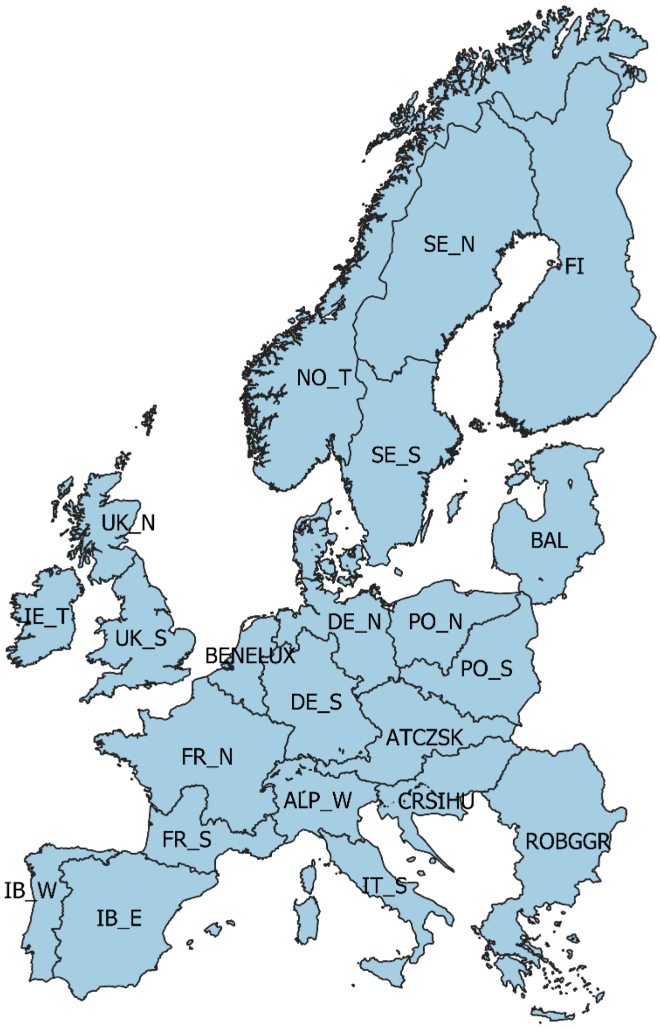

Figure A.1: Regions considered in the study.

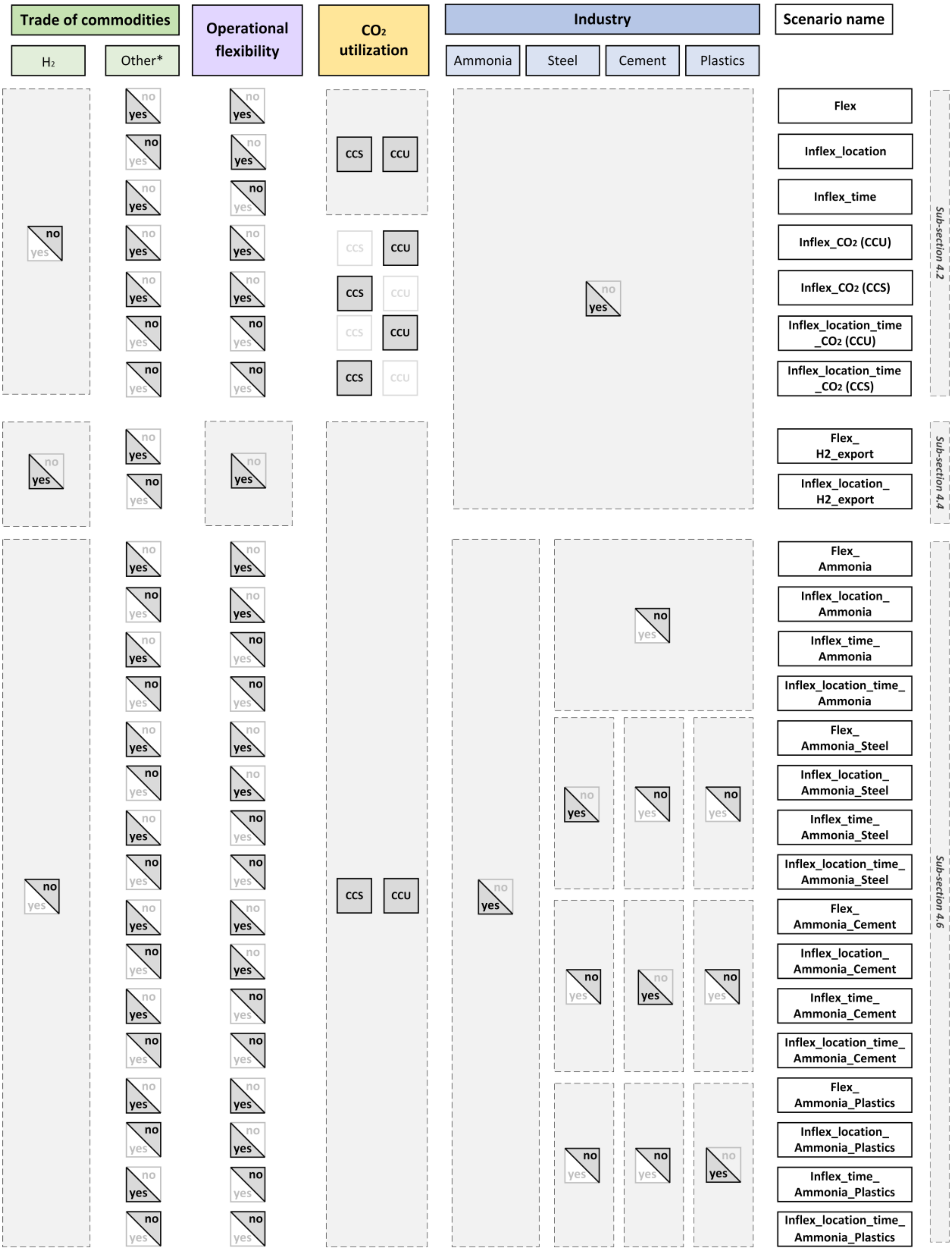

Figure A.2: Schematic overview of the parameters that define the investigated scenarios.

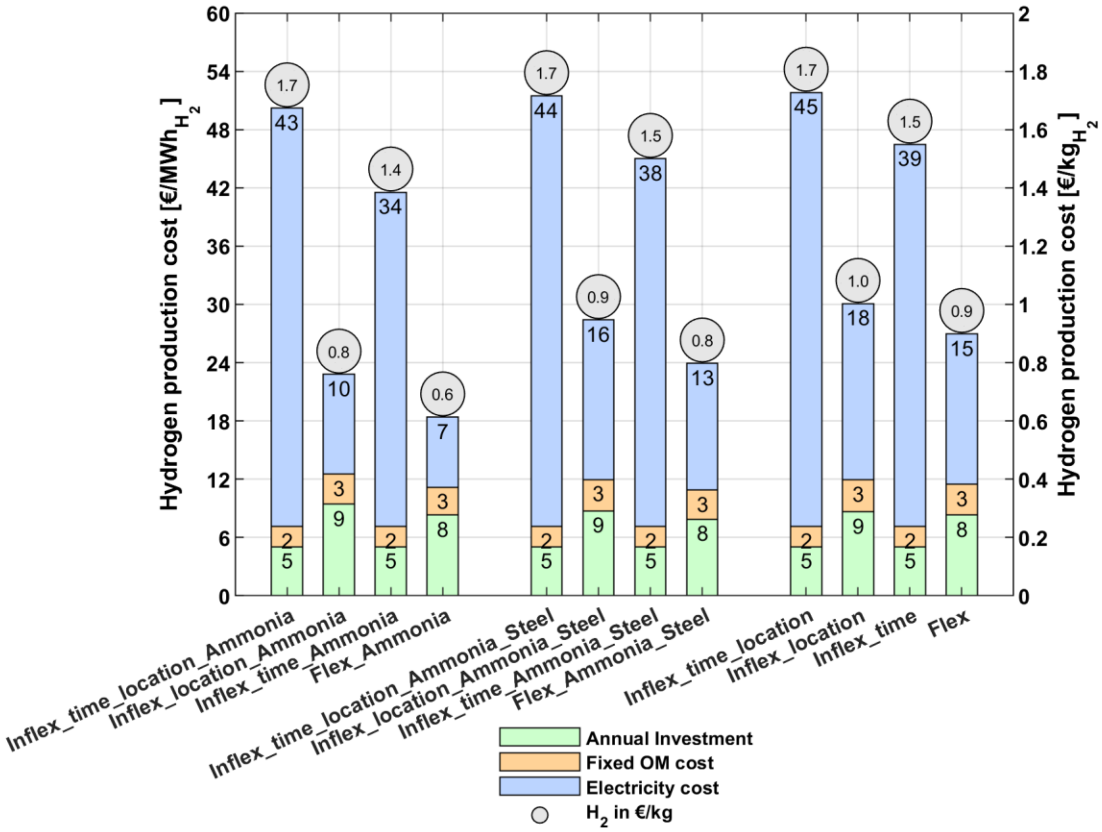

Figure A.3: The hydrogen production cost obtained from the modelling for scenarios with electrified ammonia and cement industries and for scenarios with electrified ammonia and plastics industries. Hydrogen production cost includes the annualized investment cost, fixed O&M costs, electricity cost, and hydrogen transportation costs for the investigated scenarios. This study uses an electrolyser investment cost of 550 €/kW$_{el}$.