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CO_2 Abatement in the European Industry Sector - Evaluation of Scenario-Based Transformation Pathways and Technical Abatement Measures

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Abstract

A prerequisite for achieving European greenhouse gas emission reduction targets in line with the goals of the Paris Agreement is deep emission cuts in the industry sector. In practice, this means that the economically vital, socio-politically challenging and technically heterogenous industry must perform a substantial transition within the upcoming three decades. This creates a high demand for academic methods that capture this complexity and enable the evaluation of potential industrial transformation pathways, thereby supporting informed decision making of policymakers and practitioners. Therefore, the aim of this dissertation is to develop and apply methods which enable the assessment of CO_2 abatement in the industry sector, within consistent European socio-technical energy scenarios.

In an integrated scenario process quantitative industry sector modeling is combined with qualitative scenario construction to enable the socio-technical evaluation of industrial transformation pathways. The basis for the quantitative evaluation is a European data model that captures the energy carrier and application specific structure of the European industry sector at industry branch level. Furthermore, it includes expert validated literature or primary data for modeling 27 industrial processes and the cost and potential of 131 technical CO_2 abatement measures. To process this data into pathways depicting the industrial transformation in the EU27, Norway, Switzerland and United Kingdom, the sector model SmInd EU was developed. This model enables the analysis of final consumption and consequently emission development for all 1348 NUTS-3 regions in Europe, in hourly resolution for the years 2017 to 2050. The model is designed to enable the linkage between quantitative modeling and qualitative scenario development. The disciplines of storytelling and quantitative simulation are combined in an integrated scenario process, which is applied to derive two consistent European socio-technical energy system scenarios: the climate protection scenario solidEU and a scenario named quEU, in which climate targets are not achieved.

Both scenarios as well as individual abatement measures are assessed using a holistic evaluation approach. To this end, the concept of classical or static abatement costs and their visualization in marginal abatement cost curves is revisited. The analysis uncovers disadvantages of static abatement costs which relate to a lack of data transparency, methodological weaknesses, and limited evaluation scope. Each weakness is reduced or eliminated by addressing it with a proposed set of methods. Data transparency is improved by suggesting supplementary visualizations which elicit the cost structure and perspective of abatement measures. The concept of dynamic abatement costs is then introduced, through which changes to the energy supply-side resulting from the demand-side transformation in quEU and solidEU can be considered during evaluation of the measures taken. Lastly, an adapted multi-criteria-decision-analysis is performed to identify show-stopper criteria for measure implementation (e.g., irreversible ecological damages). The combination of the developed evaluation methods builds the holistic assessment approach.

The solidEU results show that total direct and indirect CO_2 emissions could be reduced by 90 % by 2050, with respect to 1990, resulting in cumulative transformation pathway costs of 1 trillion $€_{2017}$ between 2020 and 2050. This results in average cumulative CO_2 abatement costs for the EU27+3 in solidEU between 2020 and 2050 of 75 $€/t_{CO2}$. The cost reference is the energy system in 2020. Comparing costs between quEU and solidEU is avoided explicitly. This is because the integrated scenario process reveals that the assumptions about the development of the quEU and solidEU scenario worlds differ significantly, raising serious doubts over the interpretability of cost differences between so-called reference and climate protection scenarios.

Furthermore, the SolidEU analysis demonstrates that the contribution of efficiency and electrification measures to reduce emissions decreases as emission-free synthetic fuels are phased into the energy system. This is the case because synthetic fuels lead to emission reductions in incumbent processes, thereby reducing the contribution attributed to other measures. However, waiting for synthetic fuels does not pay-off for industrial actors, since implementing climate protection measures leads to avoided costs.

Kurzfassung

Grundvoraussetzung für das Erreichen der europäischen Klimaziele sind tiefgreifende Emissionsreduktionen im Industriesektor. In der Praxis bedeutet dies, dass die europäische Industrie bis in das Jahr 2050 einen substanziellen Wandel vollziehen muss. Aufgrund der Heterogenität des Sektors besteht dabei ein hoher Bedarf nach Methoden, mittels derer industrielle Transformationsmaßnahmen und -pfade bewertet werden können, um politische und industrielle Akteure in Entscheidungssituationen zu unterstützen. Ziel ist es daher, diese Methoden zu entwickeln und anzuwenden, um die Bewertung von industriellen CO_2-Verminderungsmaßnahmen und Transformationspfaden im Rahmen konsistenter europäischer soziotechnischer Energieszenarien zu ermöglichen.

Zur soziotechnischen Bewertung industrieller Transformationspfade werden in einem integrierten Szenarioprozess quantitative Industriemodellierung und qualitative Szenariokonstruktion zusammengeführt. Grundlage für die quantitative Modellierung ist ein europäisches Daten- und Industriemodell. Es erfasst die energieträger- und anwendungsspezifische Struktur des europäischen Industriesektors auf Wirtschaftszweigebene. Darüber hinaus enthält es durch Experteninterviews validierte Literatur- oder Primärdaten zur Modellierung von 27 industriellen Produktionsprozessen sowie die technoökonomischen Kennwerte von 131 CO_2-Verminderungsmaßnahmen. Zur Berechnung industrieller Transformationspfade wird das europäische Sektormodell Industrie (SmInd EU) entwickelt. Es ermöglicht die Modellierung der industriellen Endenergieverbrauchs- und Emissionsentwicklung auf NUTS-3 Ebene in Europa und in stündlicher Auflösung für den Zeitraum 2017 bis 2050. Darüber hinaus ist die Modellstruktur durch die Implementierung einer Vielzahl von modellexogenen Parametern darauf ausgelegt, die nachvollziehbare und konsistente Quantifizierung qualitativer Szenarien zu unterstützen. In einem integrierten Szenarioprozess werden zwei konsistente, europäische, soziotechnische Energiesystemszenarien abgeleitet: das Klimaschutzszenario solidEU und das Szenario quEU, in dem die Klimaziele nicht erreicht werden.

Sowohl die Szenarien als auch einzelne CO_2-Verminderungsmaßnahmen werden mit einem ganzheitlichen Evaluationsansatz bewertet. Hierzu wird das Konzept der klassischen CO_2-Verminderungskosten erweitert. Im Rahmen der Analyse werden zunächst die Nachteile klassischer CO_2-Verminderungskosten aufgedeckt und geeignete Lösungsansätze entwickelt, um diese zu entkräften. So wird z. B. das Konzept der dynamischen CO_2-Verminderungskosten eingeführt, durch das Veränderungen auf der Verbrauchs- und Bereitstellungsseite in der Bewertung berücksichtigt werden können. Letztlich werden zusätzliche mögliche Ausschlusskriterien für die Umsetzung von CO_2-Verminderungsmaßnahmen identifiziert.

Im Klimaschutzszenario solidEU kommt es bis 2050 zu einer Reduktion der direkten und indirekten industriellen CO_2-Emissionen um 90 % gegenüber 1990. Dabei entstehen zwischen 2020 und 2050 kumulative Mehrkosten i.H.v. 1 Billion $€_{2017}$. Daraus ergeben sich durchschnittliche CO_2 Verminderungskosten für Europa im Zeitraum 2020 bis 2050 in Höhe von 75 €/tCO_2. Als Kostenreferenz wird der Zustand des Energiesystems im Jahr 2020 herangezogen. Es wird davon abgesehen eine Differenzkostenbetrachtung zwischen den Szenarien solidEU und quEU durchzuführen, da sich die Annahmen zur Entwicklung der Szenariowelten grundlegend unterscheiden. Dies erschwert die Interpretierbarkeit von Kostenunterschieden und führt dazu, dass die Aussagekraft von Vergleichen zwischen sogenannten Referenz- und Klimaschutzszenarien grundsätzlich infrage gestellt werden sollte.

Ein weiteres Ergebnis der Analyse von solidEU ist, dass der Beitrag von Effizienz- und Elektrifizierungsmaßnahmen zur Emissionsreduktion abnimmt, sobald emissionsfreie synthetische Kraftstoffe zur Verfügung stehen. Dies ist der Fall, da durch den Einsatz synthetischer Kraftstoffe bereits in existierenden Prozessen Emissionsreduktionen erzielt werden können und dadurch der Beitrag weiterer Maßnahmen sinkt. Die Kostenanalyse zeigt jedoch, dass industrielle Akteure in einem strikten Treibhausgasverminderungsszenario durch die Umsetzung von Klimaschutzmaßnahmen langfristig den Einsatz synthetischer Brennstoffe begrenzen und somit Kosten vermeiden können.

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Abbreviations

AC	Abatement cost
ACM	Abatement cost matrix
BECCS	Biomass and Carbon, Capture, and Storage
BF	Blast Furnace
BFG	Blast Furnace Gas
CC	Carbon Capture
CCS/U	Carbon Capture and Storage/Usage
CG	Container Glass
CHP	Combined heat and power
CIB(&S)	Cross-impact balance (and simulation)
COG	Coke oven gas
COP	Coefficient of performance
CS	Crude steel
CSM	Cross-sectional measures
CST	Cross-sectional technologies
DAC	Direct air capture
DPM	Descriptor-parameter-matrix
DRI	Direct reduced iron
EAF	Electric-arc furnace
EEG	German renewable energy levy
E-HVC	Electrical steamcracker
EMF	Emission factor
E-PRTR	European Pollutant Release and Transfer Register
EU ETS	European Emissions Trading System
FC	Final consumption
FEC	Final energy consumption
FG	Flat glass
FREM	FfE Regionalized Energy System Model
FWV	From Word to Value
GHG	Greenhouse gas
H&C	Heating and cooling
HVC	High value chemicals
HW	Heating and hot water
ICT	Information communication technology
IL	Intuitive logic
ISAaR	Integrated Simulation Model for Unit Dispatch and Expansion with Regionalization
ISD	Industry-site database
LPG	Liquefied petroleum gas
MACC	Marginal abatement cost curve
MCA	Multi-criteria analysis
menP/mexP	Model endogenous / model exogenous parameters
MTA/O	Methanol-to-aromatics/olefines
OPEX	Operating expenditure
O&M	Operations and Maintenance
P2MeOH/NH_3/H	Power-to-Methanol/Ammonia/heat
R&D	Research and development
(v)RES	(Variable) Renewable energy sources
SAS	Story and simulation
TEP	Theoretical electrification potential
TRL	Technology readiness level

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1 Introduction

The aim of this dissertation is to develop and apply methods which enable the evaluation of industrial CO_2 abatement pathways and measures in consistent European socio-technical energy scenarios.[1] This section explains the motivation behind the research and introduces the research questions addressed in this dissertation.

1.1 Motivation and Objective

As numerous deep emission reduction scenarios have shown, achieving greenhouse gas (GHG) emission reduction, in line with the goals of the Paris Agreement, requires deep emission cuts in all economic sectors [1]. The industry sector is the largest emitter of all energy end-use sectors, totaling 34 % of 2017 European CO_2 emissions.[2] Consequently, also this economically vital, technically complex, and heterogenous sector must achieve deep emission cuts. The necessary contribution of the European industry sector to achieving emission reduction targets is expected to lie between 90 – 95 % reduction of direct energy and process related GHG emissions with respect to the levels in 1990 [4].

To date, a common consensus on the pathway towards deep emission reduction in the European industry sector does not exist. This results from unsolved challenges and uncertainty with respect to technical, economic, and sociopolitical aspects.

Technologically, CO_2 abatement in the industry is challenged by the complexity and heterogeneity of industrial processes as well as typically long technology lifetimes. Furthermore, fundamental industrial CO_2 abatement options are often characterized by low technology readiness levels (TRL) [5]. The identification of technically realizable pathways is therefore multi-faceted and the number of viable technical mitigation pathways is high. To this end, the prevailing industrial transformation pathway literature agrees that a combination of technologies from different abatement strategy fields (e.g. energy efficiency, electrification) is required to achieve emission reduction goals in the industry [1].

From an economic perspective, the search for the most cost-efficient deep emission reduction pathway is ongoing. This search is not only challenged by technological diversity, low-cost data availability and high uncertainty, but also by differences between investor and systemic cost perspectives [6]. Thereby, the actual costs incurred to the energy system are often not reflected by the costs investors face in practice. Yet, both the investor perspective as well as the systemic perspective influence industrial transformation pathways and need to be considered during their evaluation.

In addition, these technoeconomic aspects are affected by often implicit assumptions about sociopolitical developments [7]. This poses the risk of misleading conclusions, as promising pathways from a technoeconomic perspective might only be feasible within a certain sociopolitical environment. In the existing studies [2, 8–11] with data for European industrial transformation pathways, storylines and quantitative scenario are not developed in an integrated process. Hence, an evaluation approach encompassing the different perspectives and leading to a consistent European industrial transformation pathway is required.

Industrial and political stakeholders tasked with implementing abatement measures and designing the industrial energy transition, therefore face a challenging multi-criterial decision environment. In this context,

[1] In this dissertation the terms abatement, mitigation, or reduction measure are used synonymously.

[2] Calculated based on polluter pays principle, where indirect emissions from electricity consumption are allocated to end-use sectors. Emission balancing is restricted to CO_2 gas. According to [2] direct CO_2 emissions were 75 % of total GHG emissions in the European industry sector in 2017. European refers to the EU27 plus Norway, Switzerland, and the United Kingdom (EU27+3). Furthermore, industry encompasses the industry branches listed in the Eurostat energy balances (cf. NACE Rev. 2 groups [3] listed in appendix 9.1).

it is the role of academia to develop methods which capture this complexity, and enable the evaluation of potential industrial transformation pathways, thereby supporting informed decision making in practice.

This dissertation draws inspiration from this set of multi-criterial challenges and aims at developing and applying methods which facilitate a comprehensive evaluation of industrial CO_2 abatement. Thereby, evaluating European industrial CO_2 abatement entails two elements: firstly, the analysis of individual CO_2 abatement measures; and secondly, the evaluation of industrial transformation pathways.

From a technoeconomic perspective, an evaluation is only feasible if the intra- and intersectoral effects of measure implementation are considered [6]. Interdependencies can occur between abatement measures within the industry sector and between the industry sector and the energy supply-side. For instance, the implementation of an abatement measure can impact the abatement potential and costs of another measure. Furthermore, the annual implementation potential of a measure might be restricted by maximum technology exchange rates within a sector. Measure implementation also affects the configuration and development of the energy supply-side since it is tasked with the procurement of energy. This is especially the case in deep emission reduction scenarios, in which abatement measures can trigger a vast direct or indirect demand for emission-free electricity. A necessity for the comprehensive technoeconomic evaluation of abatement measures is therefore an integrated sectoral perspective.

In the context of the energy transition of European countries this in turn results in the need for a European as opposed to an isolated national evaluation approach. A purely national perspective is insufficient for assessing the effects of industrial CO_2 abatement in the highly integrated and interconnected European energy system. Therefore, this dissertation focuses on the analysis of European industrial transformation pathways. Hereby, a key evaluation criterion is dynamic CO_2 abatement costs (ACs), which reflect the costs per unit of abated CO_2 under consideration of the intra- and intersectoral effects of measure implementation [6].

Since the concept of CO_2 abatement costs is constrained to technoeconomic aspects, further methods are developed to incorporate sociopolitical aspects in the evaluation. These include the development of consistent so-called socio-technical scenarios as well as the identification of additional criteria relevant for the evaluation of individual CO_2 abatement measures.

In the following section, the objective of this dissertation is specified further, by deriving the key research questions.

1.2 Research Questions

The objective of this thesis is to develop and apply methods for the holistic evaluation of industrial CO_2 abatement in a consistent socio-technical European industrial transformation pathway. This objective translates into two guiding research questions for this dissertation:

- How can industrial CO_2 abatement be evaluated holistically, and what further criteria are relevant for the evaluation of industrial CO_2 abatement measures besides cost and potential?
- How can qualitative context scenarios be translated into a quantitative framework to derive a consistent socio-technical European deep emission reduction scenario for the industry sector?

As described in the introduction, abatement measures and transformation pathways should be evaluated with respect to the costs of CO_2 mitigation and under consideration of additional criteria which go beyond the technoeconomic perspective. Consequently, to answer the first research questions, the concept of CO_2 abatement costs is revisited and augmented to facilitate a multi-criterial approach.

For the meaningful evaluation of CO_2 abatement, consistent European socio-technical transformation pathways need to be identified. To do so, both quantitative technoeconomic aspects as well as sociopolitical developments need to be considered. To answer the second research question, the development and application of a scenario process facilitating a consistent and integrated perspective on quantitative and qualitative industrial transformation pathways is necessary. Considering the climate targets described in section 1, this step involves the derivation of a consistent socio-technical European climate protection scenario.

To perform the holistic evaluation of European CO_2 abatement in a consistent socio-technical European industrial transformation pathway, a variety of further steps are necessary.

First, technological abatement measures which can facilitate deep emission reduction in line with climate targets need to be identified. Thereby, the costs of these measures are also relevant, to enable an economic evaluation of abatement measures and pathways. Due to the complexity and heterogeneity of European industrial processes, deriving a holistic list of measures is impractical. Hence, a method for the identification and selection of the most important technical abatement measures is developed and subsequently applied.

Second, a model capable of capturing the technical diversity of industrial processes and abatement measures, as well as the complex intra- and intersectoral effects resulting from measure implementation is required. The development of this model is therefore driven by the need to map the industry sector in Europe and at the same time provide the temporal and spatial resolution required to assess the intra- and intersectoral effects of abatement measure implementation.

Lastly, the costs of the identified European industrial transformation pathways need to be evaluated under consideration of the identified additional criteria as well as interpreted in the light of their sociopolitical context.

These three steps translate into the following research questions, which guide the work presented in this dissertation:

- How can technical CO_2 abatement measures for the industry sector be identified and quantified?
- How can the European industrial energy and feedstock consumption be modeled in high temporal and spatial resolution?
- What are the CO_2 abatement costs of a European industrial deep emission reduction transformation pathway, and which cost components drive these costs?

In the following section, an overview of the methodology derived to answer the identified research questions is provided. Considering the broad multi-criterial approach in this dissertation, it is important to note that in-depth analysis of European transport infrastructure development as well as the life-cycle-assessment of industrial abatement measures are not in-scope. Furthermore, this thesis focuses on analyzing technical industrial CO_2 abatement measures in the context of the European energy transition. The effect of policy measures or behavioral changes on the industrial energy transition is not considered.

2 Methodology

The methodology contains two sections: in section 2.1, the work in this dissertation is put into context of the broader model landscape which is used to calculate European transformation pathways for the entire energy system. This step is required since the evaluation of system effects of CO_2 abatement pathways requires the application of a larger set of models. In section 2.2, the methodology for answering the research questions and the structure of this dissertation is introduced.

2.1 European Model Landscape

As described in the introduction, one aim of this dissertation is to assess CO_2 abatement measures under consideration of the effects of measure implementation on the energy supply-side. To do so, the industry model is embedded in the model landscape shown in Figure 1. It shows the set of demand- and supply-side models applied to model holistic techno-economic energy system transformation pathways. While the clear focus of this dissertation is the industry sector, a broader understanding of the model landscape is required to fully understand how system effects are considered in the evaluation.

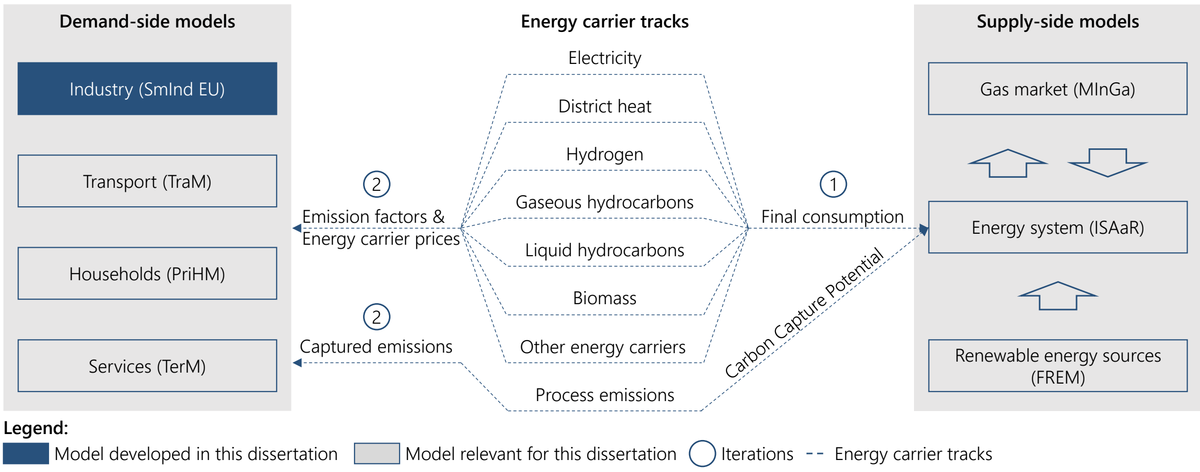

Figure 1: Model landscape for deriving system effects of abatement measure implementation[3]

Figure 1 shows that the European sector model industry (SmInd EU), which is developed in this dissertation, is one of four European sector models. These are used to derive demand-side transformation pathways in form of final consumption (FC) values and process emissions.[4] Thereby the term FC entails both final feedstock and final energy consumption (FEC). In the first iteration, these pathways are communicated to the *Integrated Simulation Model for Unit Dispatch and Expansion with Regionalization* (ISAaR) in hourly resolution at NUTS-3 level for the EU27+3. This is done via so-called energy carrier tracks [6, 12, 13, 16].

In the ISAaR simulation run, the cost-optimal pathway to satisfy the load conditions for electricity, district heat, hydrogen as well as gaseous and liquid hydrocarbons under a given GHG emission cap is determined.[5] ISAaR is a linear optimization model aimed at minimizing total system cost [6, 13]. To satisfy the load

[3] Own illustration based on [6, 12]. For more information about the demand-side model for TraM, PriHM and TerM confer [12]. For further information about the supply-side models confer [6, 13] for ISAaR, [14] for MInGa and [15] for FREM. For visualization purposes all energy carriers which are not procured via the supply-side models are summarized under *other energy carriers*.
[4] In this dissertation emissions are categorized as direct and indirect emissions. Direct emissions include the emissions which result directly from energetic fuel use or chemical reactions in processes. The latter are termed process emissions. The term indirect emissions is used when FC results in emissions on the energy supply-side (e.g., for electricity or hydrogen generation/production).
[5] To calculate total system emissions for each time interval and compare them to the GHG emission constraint level, also energy carriers not procured by ISAaR (e.g., biomass, lignite) are communicated to ISAaR.

condition, the model determines the cost-optimal European generation unit dispatch and expansion. The *FfE regionalized energy system model* (FREM) thereby provides ISAaR with detailed information about the potential capacity and costs of wind and solar power expansion.[6] Hence, the optimization algorithm determines when and where to expand the capacity of variable renewable energy sources (vRES) in the given scenario. Furthermore, ISAaR can decide to substitute fossil gaseous and liquid hydrocarbons through emission-free synthetic substitutes (SynFuels), in case this is required to clear the GHG emission reduction constraint and/or leads to a reduction of total system cost. ISAaR can also deploy carbon capture (CC) and storage (CCS) or utilization (CCU) measures. Hereby, a CC potential is communicated from the industry model to ISAaR. It reflects the potentially abatable industrial process emissions through CC measures. Ultimately, ISAaR is also connected to MInGa, which calculates the cost optimal procurement of natural gas. MInGa is a linear optimization model which minimizes the total costs of gas procurement in Europe. It analyses European gas flows as well as the changes in gas prices in each scenario.

The hourly energy production values as well as costs resulting from changes to the supply-side are evaluated to derive emission factors, energy carrier prices, and the share of abated process emissions.[7] The calculated values reflect the changes in emissions and costs induced to the supply-side as a result of demand-side transformation pathways. In the second iteration (cf. Figure 1), this information is communicated to the demand-side models, thereby enabling the evaluation of abatement measures and transformation pathways under consideration of the resulting system effects.

Through the model iterations described above, the so-called dynamic evaluation of costs and emissions resulting from demand-side transformation pathways is enabled [6]. This however requires the quantification of scenarios which describe the entire energy system. The scenarios developed in this dissertation are consequently not restricted to the industry sector, but always describe full energy system transformation pathways. Therefore, the resulting energy carrier prices and emission factors are not solely a result of the assumed industrial transformation but are also influenced by developments in other sectors. For this dissertation explanations and analysis are confined to the industry sector. References and explanations relating to the broader model and scenario context are provided where they are required to understand parts of the methodology or results.

2.2 Modeling and Evaluation of CO_2 Abatement in the European Industry Sector

In this section, the methodology and structure of this thesis required to answer the research questions in section 1.2 are explained. The main components of this dissertation and the applied method set are depicted in Figure 2.

In section 3 the EU industrial data model is constructed. While the aim of this section is the identification, selection, parametrization, and quantification of industrial abatement measures, the intermediate steps provide industry branch and process data for modeling the European industry sector. In the first step, the European industrial energy carrier and application balance is developed. The latter balances the FEC by industry branch, energy carrier, and application for each EU27+3 country. This provides direct input for the final consumption module of SmInd EU and poses the basic quantitative framework of the model. Furthermore, this data supports the analysis of the energy industry structure in the EU27+3. It is consequently the basis for selecting the most energy and emission intensive industry branches for further in-depth analysis. In step two of the EU industrial data model, energy and emission intensive industrial processes are identified for the previously selected industry branches. The derived process data is direct input to SmInd EU and provides the basis for identifying the most promising deep emission reduction

[6] FREM can be used both as a calculation tool as well as a database. In this dissertation it is predominantly used as a database to store and extract input data and results. With reference to Figure 1, FREM contains the information and algorithms to derive the potential and costs of capacity installation for vRES and serves as the database used to communicate between models.
[7] ISAaR and MInGa results are only necessary to derive future scenario results for energy carriers procured by elements depicted in these models. Solid fuel energy carrier prices for example are not determined based on supply-side model results.

measures. The latter is part of the third and last step of constructing the EU industrial data model, in which a method for the identification, selection, parametrization, and quantification of industrial abatement measures is derived and applied.

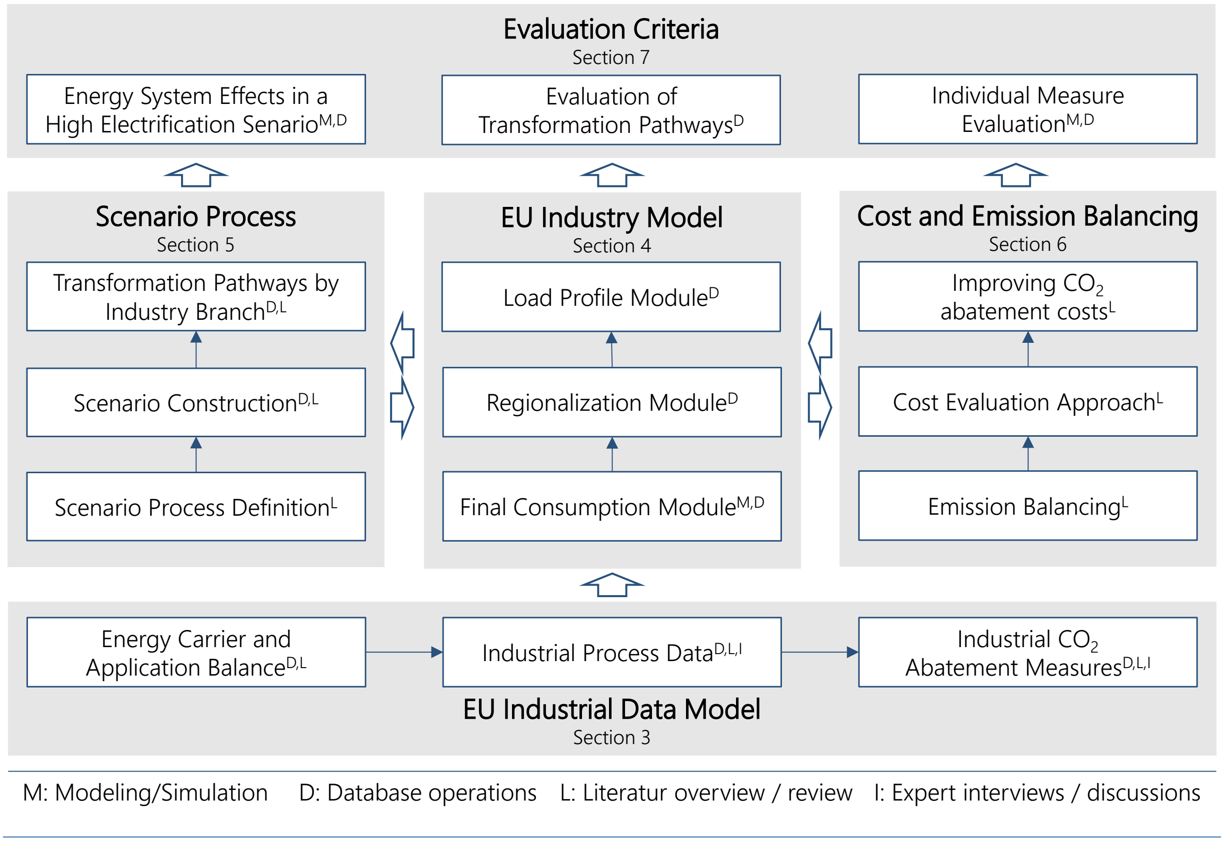

Figure 2: Components and method set for evaluating industrial CO_2 abatement in Europe

In section 4 the method for modeling the European industrial energy and feedstock in hourly resolution at NUTS-3 level is explained. SmInd EU is structured into three modules. First, annual and country specific (NUTS-0) industrial final consumption and process emissions are calculated until 2050. For this step, the industry branch, process, and abatement measure input data described in section 3 are used. Subsequently, the FC and process emissions are regionalized and then scaled with normalized load profiles, to provide FC time-series in hourly resolution at NUTS-3 level. The combination of results from the final consumption, regionalization and load profile modules enables the analysis of final consumption and consequently emissions for all 1348 NUTS-3 regions in Europe, in hourly resolution. As shown in section 2.1, SmInd EU is embedded in a European model landscape.

In section 5, an integrated scenario process is developed and applied to derive two industrial transformation pathways named quEU and solidEU. Thereby, quEU is a scenario in which European climate targets are not fulfilled. SolidEU on the other hand poses a deep emission reduction scenario in which, across all sectors, 95 % GHG emission reduction with respect to 1990 will be achieved by 2050. As described in section 2.1, this step is performed for the entire energy system, but only the components relevant for the industry sector are discussed in this dissertation. Each transformation pathway is characterized by a qualitative storyline and a quantitative scenario. Thereby, the qualitative scenario provides a scenario framework which facilitates the plausible quantification of SmInd EU model parameters. To ensure the consistency between the quantitative and qualitative scenario components, the so-called *From Word to Value* (FWV) procedure is developed and applied. The FWV procedure structures the quantification of qualitative storylines, thereby facilitating increased traceability and consistency of the sociopolitical and technoeconomic developments in scenarios. The section concludes with the quantification of scenario-dependent SmInd EU parameters including a description of the industry-branch specific transformation pathways for quEU and solidEU.

In section 6 the balancing areas for emission and cost evaluation for individual measures and transformation pathways are introduced. This step ensures that results are not only interpreted with respect to the scenario worlds created in section 5, but also delimits the analyzed emission and cost components. Cost and emission evaluation is focused on deriving CO_2 abatement costs for individual measures and transformation pathways. To this end, the concept of CO_2 abatement costs is revisited, and its explanatory power analyzed. To improve the interpretability of CO_2 abatement costs, suggestions to counteract their limitations are introduced. This includes the identification of additional relevant criteria for evaluating CO_2 abatement measures using an adjusted multi-criteria analysis (MCA) approach. Hereby, especially so-called *show-stopper* criteria are identified, which can lead to the exclusion of measures from further analysis.

In section 7, the previously introduced methods are used to evaluate the scenarios quEU and solidEU. The evaluation is structured into two steps: firstly, an individual CO_2 abatement measure analysis is performed; and secondly, the transformation pathways for quEU and solidEU are evaluated. In both cases the analysis focuses on CO_2 abatement cost evaluations under consideration of the sociopolitical context of the respective scenario worlds as well as the identified show-stopper criteria. Amongst others, the aim of this section is to evaluate the transformational cost of quEU and solidEU as well as discuss to what extent a scenario comparison is purposeful. Since a Europe-wide evaluation of abatement scenarios on energy system transport infrastructure such as transmission networks is not in the scope of this thesis, the section is concluded by an excursus. A case study for an extreme electrification scenario for Germany in 2030 is discussed. This aims at displaying how the effects of measure implementation on the transmission grid and the energy supply-side can be analyzed.

The dissertation is finalized with section 8, in which conclusions from developing and applying the methodology are drawn, its limitations are discussed and ideas for further research are postulated.

3 European Industrial Data Model

To analyze industrial CO_2 abatement in the European industry sector, a European industry data model is constructed. This model contains scenario-independent data used to depict the energy and emission-related status quo of the European industry and the associated technical CO_2 abatement options. Scenario-dependent data, such as projections about the future economic development, or the depth and breadth of CO_2 abatement measure implementation, are discussed in section 5.2. Figure 3 provides an overview of the components and structure of the European industrial data model.

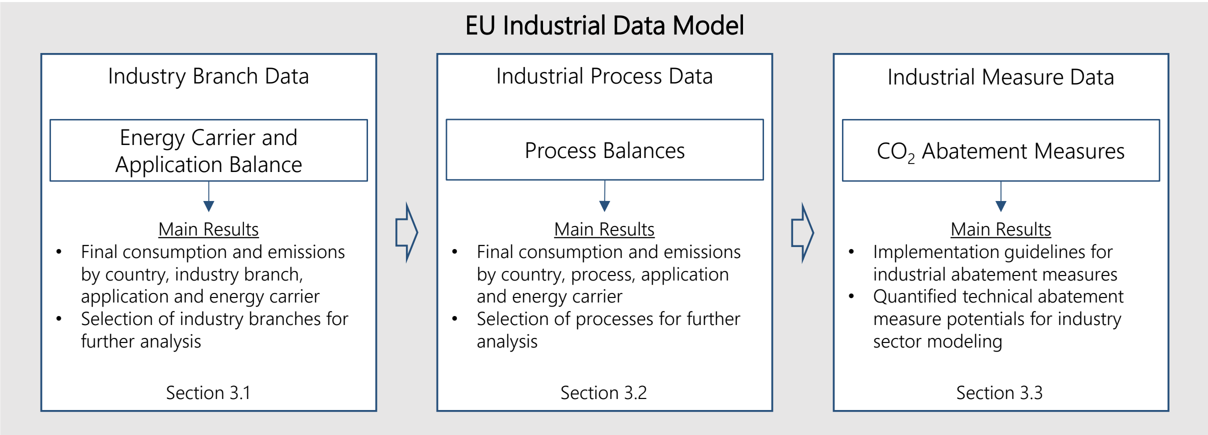

Figure 3: Components and structure of the EU industrial data model

A step-wise procedure is followed to derive the data model. Each component of the data model is simultaneously a direct input for the final consumption module of the industry model SmInd EU (cf. section 4). Step 1, the European industrial energy carrier and application balance, provides FEC data for each country, industry branch, energy carrier and application (cf. section 3.1) [17]. It serves as the basic quantitative framework for modeling industrial transformation pathways. Furthermore, it is the basis for identifying the most energy and emission intensive industry branches and applications. Within the selected industry branches the most energy-intensive processes are identified in section 3.2. For these processes, final energy, feedstock consumption and process emissions are calculated by country [6, 18, 19]. This data serves as direct input for bottom-up modeling of industrial processes in SmInd EU. Furthermore, process-step-specific energy and emission balances are constructed using this data. These process balances, as well as the European energy carrier and application balance, are part of the identification procedure for greenhouse gas abatement measures in step 3. Thereby, measures are defined for the previously selected applications and processes (cf. section 3.3) [19].

3.1 Energy Carrier and Application Balance

The starting point for the development of industrial transformation pathways as well as the subsequent selection of energy and emission intensive industry branches and processes is the European industrial energy carrier and application balance [20, 21]. The latter provides annual industrial FEC by country, industry branch, energy carrier and application for the base year 2017. As shown in [22] only seven countries in the EU27+3 provide detailed energy application statistics. To determine a consistent starting point for calculating industrial transformation pathways, national energy application balances for all EU27+3 countries are calculated using a homogenous data set. To do so, energy application shares are calculated for all countries and industry branches. They are then scaled with absolute 2017 FEC data from Eurostat energy balances [23]. The resulting European energy carrier and application balance is referred to as top-down FEC in this dissertation.

Energy application shares are derived based on the balances for heating and cooling (H&C) applications in [22]. To balance the entire industrial FEC by energy carriers and applications and allow for a more accurate subsequent emission calculation, the shares derived from the H&C balances are expanded. In addition, more detailed coal and gas energy carriers as well as cross sectional technology (CST) applications are added. The full set of energy carriers and applications is shown in Table 1.

Table 1: Energy carriers and applications in the energy carrier and application balance

	Existing in [22]	Added in this dissertation
Energy carriers	electricity, fuel oil, natural gas, renewable waste, non-renewable waste, district heat, biomass, other fossil fuels	hard coal, lignite, coke, peat, blast furnace gas, coke oven gas
Applications	space heating, hot water, low process heat <100 °C, medium process heat 100 °C – 500 °C, high process heat >500 °C, process cooling, space cooling	information communication technology, mechanical energy, lighting, pumps, compressed air

First H&C are expanded by CST applications. To do so, the share of final energy consumption for H&C applications in 2012 is derived from [22, 24].[8] It is assumed that the electrical share of H&C applications in each country corresponds to the total FEC share and that CST applications are powered by electricity [22]. Hence, the electricity not consumed by H&C applications is allocated to CST applications. Subsequently, German energy application balances are used to determine electricity shares for the CST applications *information communication technology (ICT)*, *mechanical energy* and *lighting*, *pumps* and *compressed air* [25]. Due to the lack of more specific data, these shares are assumed for all countries and industry branches. The base year for this step is 2017 and annual updates of these shares are possible.

Second, the energy carriers *coal* and *other fossil fuels* balanced in [22] are disaggregated to *hard coal, lignite, coke oven coke, blast furnace gas (BFG)* and *coke oven gas (COG)*. This is done based on the FEC shares of these energy carriers in the Eurostat energy balance [23]. Since more detailed data is unavailable, the disaggregated energy carriers assume the same distribution to applications as the original aggregated energy carriers (i.e., coal and other fossil fuels).

Figure 4 shows the aggregated balance for all EU27+3 states. By expanding the H&C balances, a total of 12 applications and 14 energy carriers could be included in the European energy carrier and application balance for 2017.

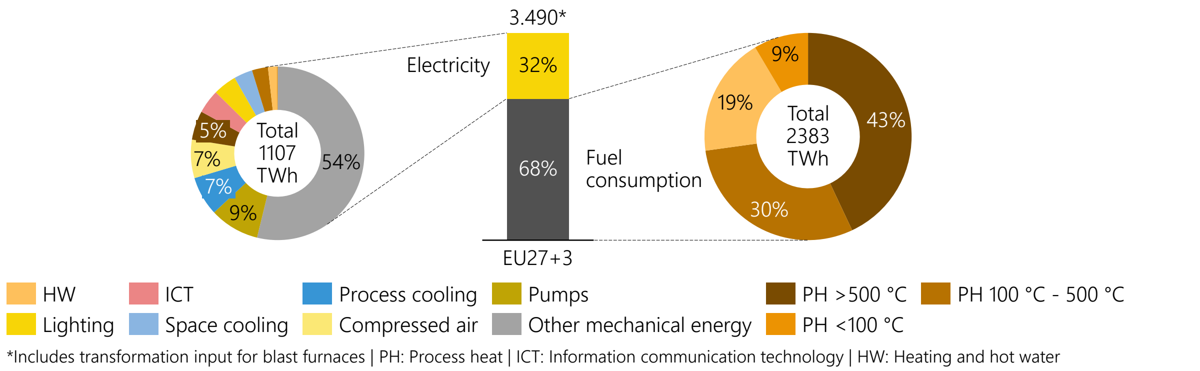

Figure 4: Industrial energy carrier and application balance for the EU27+3, 2017[9]

European industrial FEC was 3490 TWh in 2017. Hereof 32 % are electrical FEC which predominantly originates from the CSTs. Fuel consumption is dominated by process heat, with a total share of 68 % in the EU27+3. Hereby, high temperature process heat >500 °C dominates with a share of 43 %. The energy

[8] 2012 is the most recent year for which FEC data for H&C applications exists.

[9] Own illustration based on [6, 21]. For visualization purposes, non-electricity energy carriers are aggregated and displayed as *Fuel*.

carrier and application structure indicates that to reduce direct fuel emissions abatement measures addressing heating applications are required. Indirect emissions from electricity consumption afford predominantly electrical efficiency measures addressing CST. Due to the homogeneous technology structure behind CST applications, an industry branch specific analysis of these applications is not necessary to identify abatement measures. This however is not valid for process heat applications, where FEC originates from heterogeneous industrial process technologies. To derive which processes are most relevant for the modeling of industrial transformation pathways, the energy carrier and application data is combined with emission factors to determine the industrial emissions by industry branch and country, as shown in Figure 5.

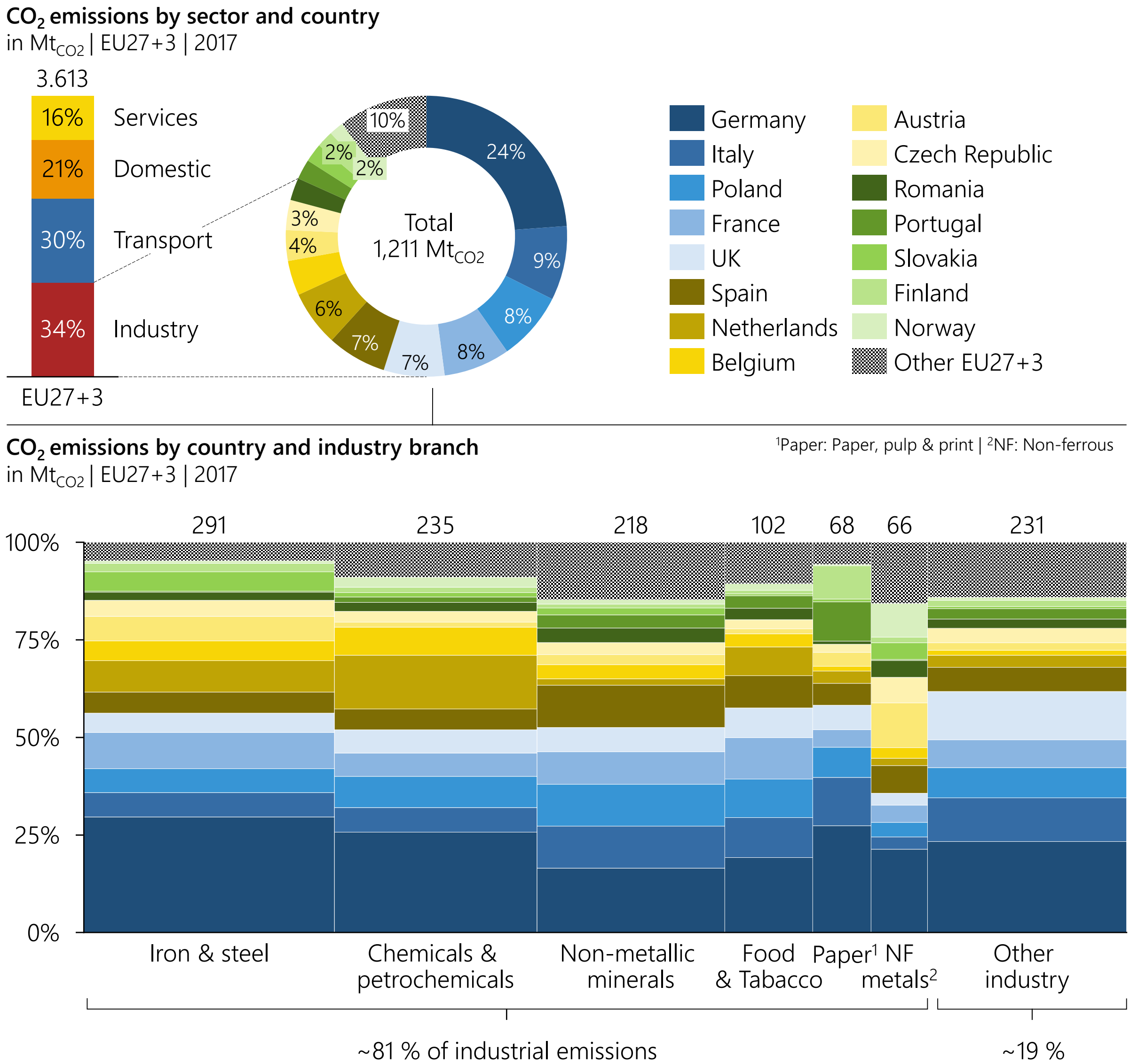

Figure 5: EU27+3 total CO_2 emissions by industry branch in Mt CO_2, 2017[10]

Figure 5 shows that the industry sector poses 34 % of total CO_2 emissions in the EU27+3. Of the 1,211 Mt_{CO2}, 24 % are emitted by German industry. Italy, Poland and France together are responsible for approximately the same amount of industrial emissions as Germany, highlighting the decisive role that the German

[10] Own illustration based on [21]. Energy consumption data mainly from [23]. Emission factors taken from national inventory reports of the respective countries: e.g. [26] for Germany. Process emissions from [27]. Balancing according to polluter pays principle. District heat emission factors calculated based on primary energy input (cf. [20]).

industry plays in European decarbonization efforts. In the EU27+3 the 10 largest industrial pollutants are responsible for ~80 % of CO_2 emissions.

The bottom half of Figure 5 indicates that 81 % of energy and process related emissions in the EU27+3 industry sector result from only five industry branches: *Iron & steel* (24 %), *Chemical and petrochemical* (19 %), *Non-metallic minerals* (18 %), *Food and tobacco* (8 %), *paper, pulp and print* (6 %) and *non-ferrous metals* (6 %).[11] Slight differences in the rank order of industry branch emissions exist between countries (e.g. Germany's large machinery industry branch ranks fourth in Germany). In general, emission shares of each industry branch are however relatively consistent compared to the EU27+3 total. On average, the industry branches iron & steel, chemical and petrochemical and non-metallic minerals emit 60 % of the industrial emissions in the EU27+3 states. Since this dissertation focuses on the European industry sector, the selection of industry branches for further analysis is therefore based on aggregated data for the EU27+3.

In addition to absolute energy consumption and emissions GVA is relevant for determining the importance of an industry branch to an economy. Hence, emission and energy intensity are considered as additional selection criteria according to Figure 6.

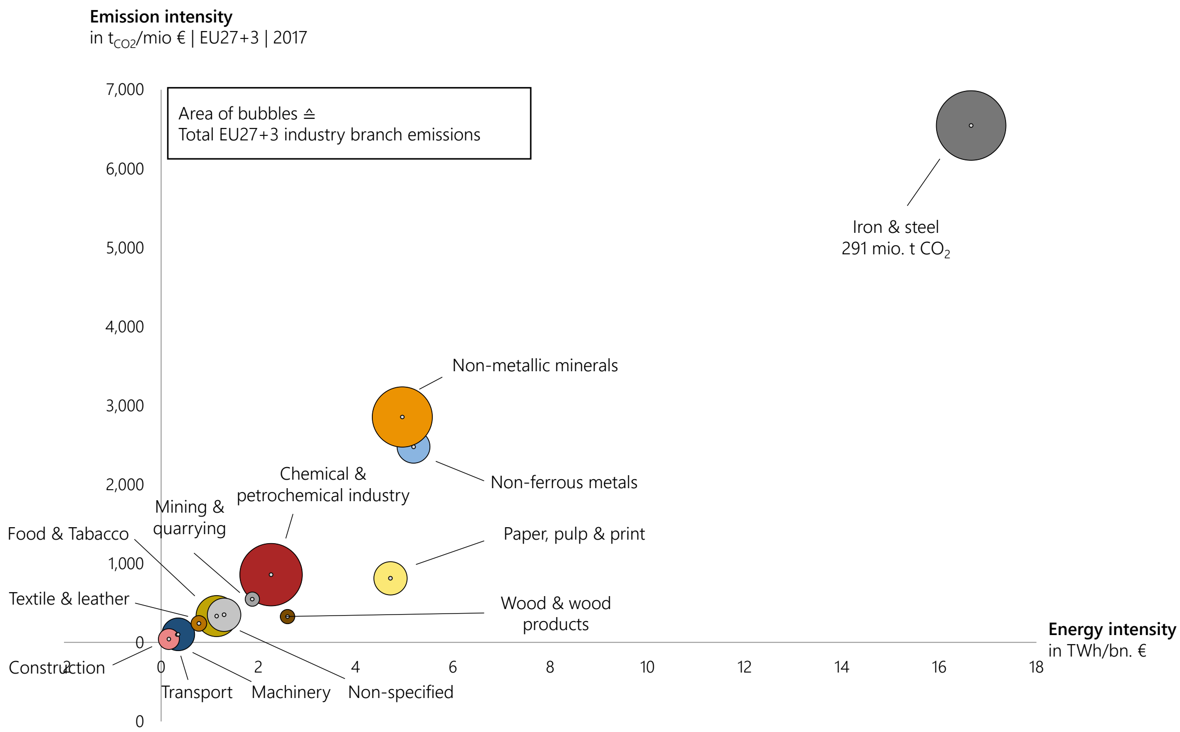

Figure 6: Energy and emission intensity by industry branch for the EU27+3, 2017[12]

Figure 6 shows that energy and emission intensity are correlated and that consequently both absolute emissions and energy consumption are suitable criteria for selecting industry branches for further analysis. Based on the intensity values as well as absolute energy consumption and emissions, the industry branches iron & steel, chemical & petrochemical industry, paper, pulp & print, non-ferrous metal industry, non-metallic minerals and food and tobacco are selected.[13] Since industry branches are statistical groups summarizing data for a variety of heterogeneous industrial processes, a further analytical step is required

[11] The industry branch definition is shown in appendix 9.1. Iron & steel, Chemicals & petrochemicals, Non-metallic minerals, Non-ferrous metals as well as Paper, pulp & print are characterized as energy-intensive [28].

[12] Own illustration based on [29]. Intensity calculated using gross value added, which is calculated as the difference between production value and intermediate consumption [30]. Data taken from [31].

[13] Mining & quarrying as well as wood & wood products are excluded from the analysis due to low absolute emissions.

to determine which technologies are the root cause of FC and emissions. This is a prerequisite for identifying the largest levers for emission abatement in process heat applications.

3.2 Process Balances

Balancing final consumption on process level serves two purposes. Firstly, it supports the identification of process specific abatement measures. Secondly, it is the starting point for modeling industrial transformation pathways on the process level. FC at the process level is referred to as bottom-up in this dissertation.

The most energy and emission intensive processes in the selected industry branches are identified based on [32]. Thereby, the selection of processes for further analysis is performed under the assumption that industrial plants have a similar technical standard across Europe [22].[14] In total, 19 energy and emission intensive industrial processes are selected for the identification of process-specific CO_2 abatement measures and subsequent bottom-up modeling of transformation pathways in SmInd EU.[15] For both purposes, energy carrier and application balances on process level are constructed. In addition, feedstock consumption and process emissions are balanced.

To derive these balances, annual production tonnages are multiplied with specific consumption data according to expression (3-1) [17, 33].[16] This is done for the different *energy carrier types*; fuel, electricity and feedstock. Expression (3-2) is subsequently used to disaggregate specific consumption for each energy carrier type to energy carrier level using energy carrier shares [33]. The latter are country, process, energy carrier type and time dependent. This two-step procedure is required because specific consumption data provided in the respective literature is given at the energy carrier type level and not energy carrier specific. The sum of all energy carrier shares for each region, process, energy carrier type and time interval (year) equals one. Fuels are disaggregated to 14 energy carriers. Furthermore the transformation relevant feedstocks naphtha, hydrogen, methanol, and liquefied petroleum gas (LPG), are included [34].[17]

$$fc_{r,b,p,t,ect} = pt_{r,b,p,t} \cdot sc_{r,b,p,t,ect} \ \ with \ \ ect \ \in fuel, electricity, feedstock \tag{3-1}$$

$$fc_{r,b,p,t,e} = fc_{r,b,p,t,ect} \cdot ecs_{r,b,p,t,ect,e} \ \ with \ \ ect \ \in fuel, electricity, feedstock \tag{3-2}$$

fc: final consumption	pt: production tonnage	sc: specific consumption	ecs: energy carrier shares
r: Region	b: Industry branch	p: process	t: Year
ect: energy carrier type	e: energy carrier		

In expressions (3-1) and (3-2) country specific values for production tonnages and, where available, for specific consumption values and energy carrier shares are used to determine process final consumption. Where country-specific values are unavailable or significantly outdated, European average or German values are applied. Process consumption is allocated to applications according to [35].

To derive total emissions from the production of goods in a process, energy and process related emissions are aggregated using expression (3-3) and (3-4). Energy related emissions on process level are calculated by scaling FEC by energy carrier with the respective emission factors. Process related emissions are derived based on production tonnage and process specific emission factors [33].

[14] Confidential communication with industry experts has shown that plant specific differences exist but depend mainly on the age and not the location of industry plants.

[15] Primary, secondary and direct reduced iron steel, olefines (Ethylene and Polyethylene), aromatics (Benzene, Toluol and Xylol), ammonia, methanol, chlorine, cement, lime, container and flat glass, dairy, paper, recycled paper, wood and chemical pulp as well as primary and secondary aluminum.

[16] Cf. appendix 9.3 for country-specific process data.

[17] Based on the German feedstock balance in [34] this covers ~50 % of fossil feedstock and therefore ~25 % of total feedstock.

$$em_{r,b,p,t} = eem_{r,b,p,t} + pem_{r,b,p,t} = \sum_{e} (fc_{r,b,p,t,e} \cdot emf_{r,t,e}) + pt_{r,b,p,t} \cdot emf_{p} \tag{3-3}$$

em: CO2 emissions eem: energy related CO2 pem: process related CO2 emf: emission factor

Before the process final consumption is used as input for the derivation of process-step-specific energy and emissions balances, consistency between the balancing areas of process data and the energy carrier and application balance is established. This is done to avoid double balancing and misallocation of final consumption. This step is especially relevant for processes which both consume and transform energy (e.g., primary steel) and/or use the same feedstock for energy and non-energy use (e.g., steamcracking). In both cases, misallocation of final consumption and/or process emissions can occur if discrepancies between bottom-up and top-down balancing areas exist (cf. appendix 9.2 for further details). Figure 7 shows the degree of bottom-up industry branch coverage through processes modeled in SmInd EU, after calibration.

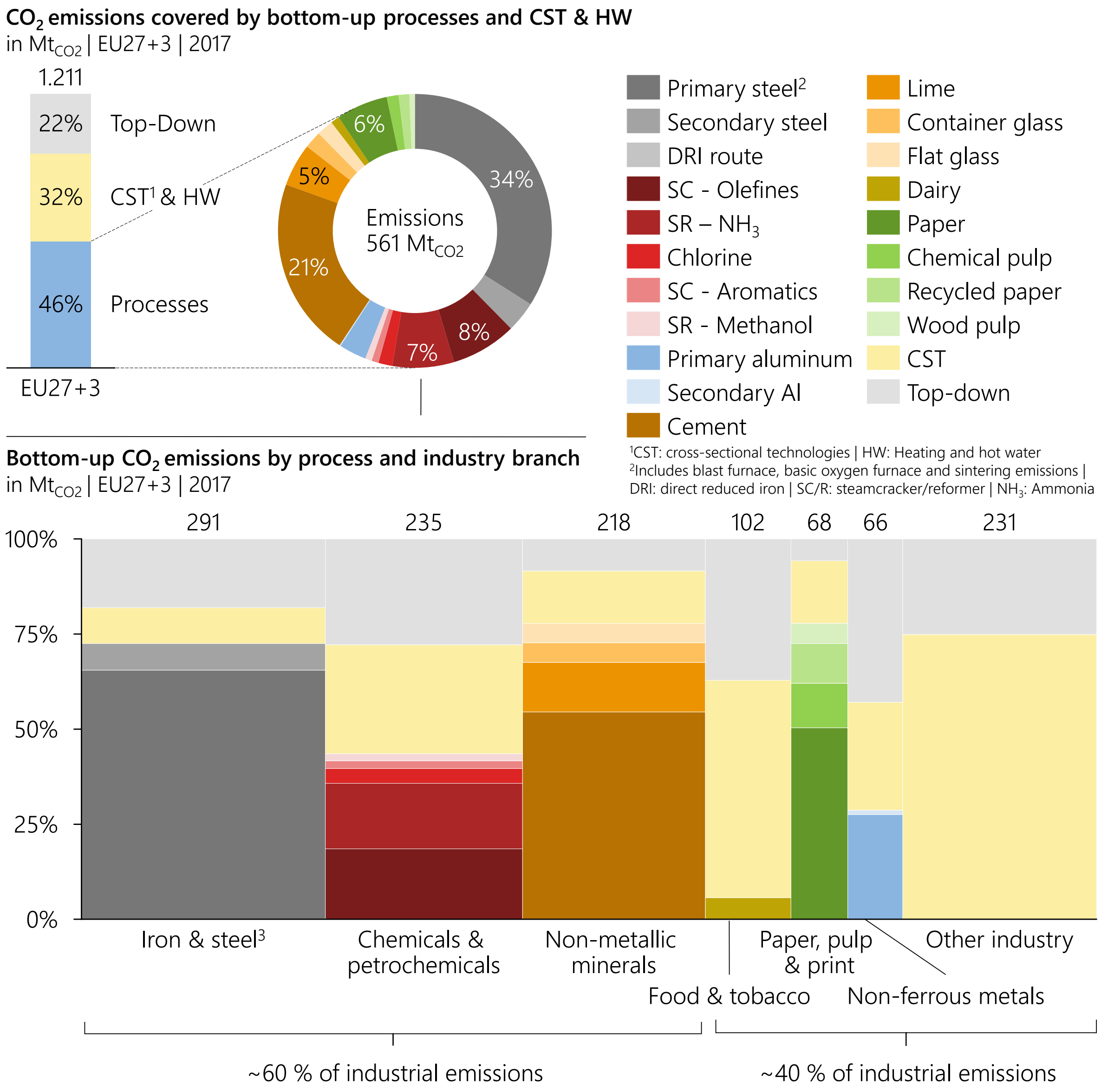

Figure 7: EU27+3 emissions covered by SmInd EU processes and CST & HW in Mt_{CO2}, 2017

The figure shows that emissions can be subdivided into three categories which reflect how these emissions are addressed in this dissertation: processes, CST & heating and hot water (HW), and top-down.[18] 46 % of European industrial emissions are covered through the bottom-up modeling of 19 industrial processes. This equates to 44 % of FEC (cf. Attachment 2 in the appendix). Furthermore, 32 % of industrial emissions result from CST & HW and can therefore be allocated to a specific technology. Hence, 78 % of European industrial emissions are directly connected to a specific technology, which is a prerequisite for determining detailed abatement measures and transformation pathways. The remaining 22 % are addressed through the top-down energy carrier and application balance.

The bottom half of Figure 7 depicts the share of process and CST & HW coverage by industry branch. In general, higher heterogeneity of industrial processes summarized within an industry branch results in lower process coverage. Furthermore, the share of CST & HW is typically higher in industry branches with lower energy and emission intensities. Including both processes and CST & HW, the share of emissions connected to a specific technology ranges from 57 % for the non-ferrous metal industry to 94 % in the paper, pulp and print industry branch.

For each of the industry branches selected in section 3.1 the process with the highest absolute emissions and emission intensity are modeled bottom-up (e.g., steel, cement, lime, paper). A trade-off between significance of the industrial process for emission abatement in the European industry sector and data collection effort is made. For example, the industry branch food & tobacco encompasses a heterogenous set of low-temperature processes ranging from the production of milk, meat, bread, beer and sugar to very granular processes such as the preservation of fish or fruit or the manufacture of starches and starch products [36]. In this dissertation only the largest emitter, dairy production, is selected for bottom-up modeling, since the other mentioned processes exhibit comparably low absolute emissions [32]. Furthermore, in this dissertation, an emphasis is laid on modeling processes in which deep emission reduction requires specific technological transformation strategies (e.g., steel, high value chemicals). The processes in the food & tobacco industry are characterized by a similar decarbonization challenge, since fuels are mostly consumed for hot water and steam production used for low-temperature process steps such as brewing and drying [32]. Process specific solutions, however, are mainly required for medium to high temperature processes [37]. This explains higher degrees of coverage in industry branches with predominantly high-temperature processes (e.g., iron & steel) compared to low-temperature process industry branches (e.g., food & tobacco).

Succeeding the balancing of FEC and emissions at process level, each process is sub-divided into its main process steps, to identify which appliances pose the largest energy consumers and emitters and are consequently most relevant for emission reduction. This is exemplified by the cement production process depicted in Figure 8. The diagram shows that the cement production process consists of four main process steps [29, 32, 38]:

1. Extraction of limestone, chalk or clay in mines using explosives
2. Crushing, homogenization (in mills) and drying of raw materials
3. Burning of clinker in rotary kilns at approximately 1450 °C
4. Cement grinding in ball, vertical or material bed roller mills

Electrical FEC in cement production mainly results from the grinding of raw materials and cement, while fuel consumption stems predominantly from the burning of clinker. The process step analysis shows that clinker burning and therefore the rotary kiln are the main source of energy consumption and emissions in cement production. Hence, the abatement measure identification efforts mainly focus on this process step.

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[18] HW are grouped together with CST since HW is also characterized by homogenous technologies and low technical complexity. Like CST, measures for mitigating emissions from HW consequently do not require an industry branch or process specific analysis.

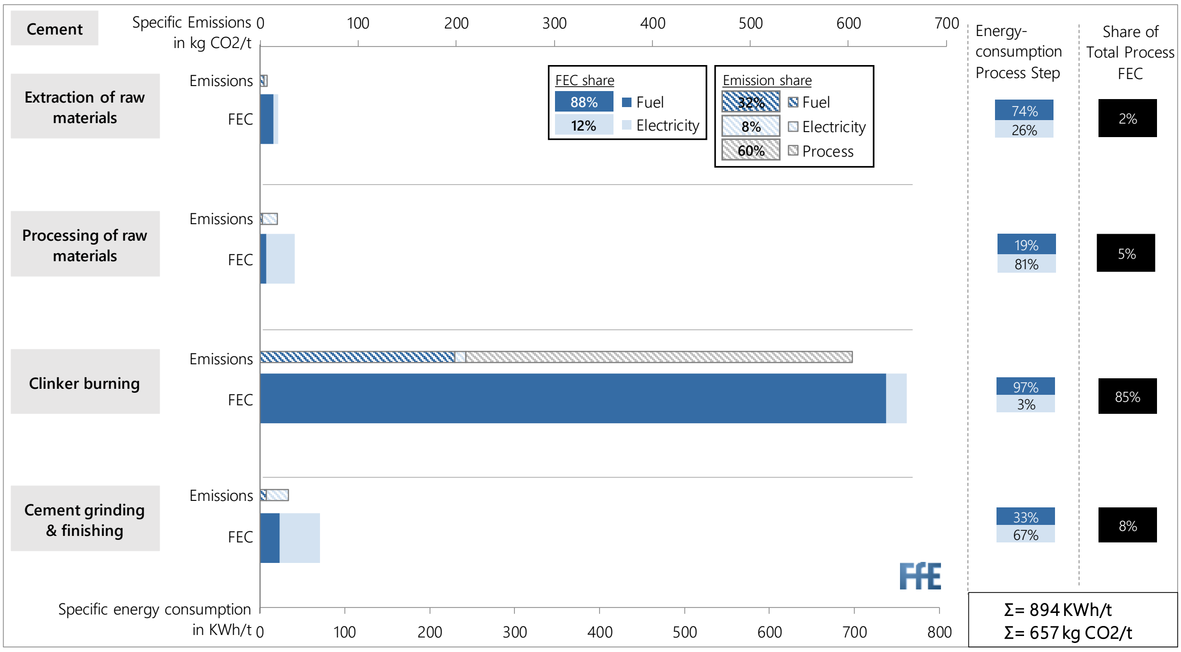

Figure 8: Energy and emission balance by process-step for German cement production[19]

In the following sections an overview of the status-quo of the selected industry branches and processes is provided. Hereby, the factors and challenges most relevant for deep emission reduction in each process are summarized. Brief process descriptions and process-step specific balancing of specific energy consumption and emissions are provided in Appendix 9.4.

Iron and Steel

The **iron and steel** industry branch, as reported by Eurostat, encompasses the NACE rev. 2 groups 24.1, 24.2, 24.3, 24.51 and 24.52 (cf. Attachment 1 in the appendix). EU27+3 gross value added in this industry branch was € 44.4 bn in 2017, which equals a share of 2 % of total GVA [31]. In SmInd EU, the primary and secondary steel production processes as well as the existing direct reduced iron (DRI) plant in Hamburg, Germany and the pilot plant in Lulea, Sweden are modeled bottom-up.[20] These crude steel (CS) production processes cover 73 % of the 291 Mt_{CO2} in the iron and steel industry. Processes not covered bottom-up mainly include the production of rolled steel and casting of steel. Table 2 summarizes key aspects of the steel industry.

Table 2: EU27+3 steel production overview for 2017[21]

Steel production route	Number of furnaces	Crude steel production	Avg. energy demand	Direct CO_2 emissions	Indirect CO_2 emissions
	#	Mt_{CS}	GJ/t_{CS}	Mt_{CO2}	Mt_{CO2}
Primary	29	101	15	185	5.3
Secondary	132	69	3.3	6.8	14
DRI	2	0.7	10	~0.3	~0.2

[19] Own illustration based on [19, 29]. A clinker-cement factor of 0.77 is assumed.

[20] The DRI plant in Hamburg is operated with natural gas. The pilot plant in Sweden operates using Hydrogen [5]. The mentioned processes belong to NACE rev. 2 group 24.1.

[21] Number of furnaces derived from [39–41]. For country specific data and references cf. appendix 9.3. Direct emissions include direct energy related and process emissions.

In the EU27+3 crude steel production totaled 171 Mt_{CS} in 2017. Total emissions from steel production in the EU27+3 in 2017 were ~212 Mt_{CO2}. This includes direct emissions from fuel combustion and chemical reactions in industrial processes (process emissions) as well as indirect emissions from electricity consumption.

In the EU27+3 ~101 Mt_{CS} were produced at 29 integrated steelwork locations causing total emissions of 190 Mt_{CO2}. Direct emissions in the primary production route totaled 185 Mt_{CO2}, resulting predominantly from the use of hard coal, coking coal and blast furnace gas as energy carriers and reduction agents in the blast furnace (BF). During steel production, the reduction of iron ore to pig iron in the BF causes process emissions. In the BF temperatures of up to 2200 °C are reached. This poses the most energy and emission intensive production step in primary steel production. With an average scrap share of 8 % in the EU27+3, specific emissions in the blast furnace amount to ~1.6 t_{CO2}/t_{CS}. Total specific emissions in primary production are ~1.9 t_{CO2}/t_{CS}. Energy demand for primary steel production ranges from ~14 GJ/t_{cs} in Hungary to 16 GJ/t_{cs} in Italy, with an average of 15 GJ/t_{CS} in Europe.[22]

Secondary production occurred in 132 scrap-based electric arc furnaces (EAF), in which temperatures of up to 3,500° C are generated. With a scrap share of more than 95 %, the production of ~69 Mt_{CS} in the less energy intensive secondary steel production route caused ~21 Mt_{CO2} emissions in 2017. This translates to specific emissions for secondary steel production of ~0.3 t_{CO2}/t_{CS}. Hereof ~67 % were indirect emissions from electricity consumption and ~33 % were direct emissions. The latter mainly emerge from the electrode burn-off, decarburization and the pre-heating of the charge via natural gas fired burners [43]. Hence, also secondary steel production is associated with process emissions. The expansion of the secondary steel production route is limited by the availability of (high quality) steel scrap [44].

DRI steel was produced at two locations in 2017 (~0.7 Mt_{CS}) but has not reached industrial scale to date. In comparison to the primary and secondary production route DRI steel emissions in the EU27+3 are consequently negligible: ~0.5 Mt_{CO2}. However, this production route poses a promising deep emission reduction possibility for steel production. Currently electricity and natural gas are the main energy carriers and reduction agents. However, future DRI steel production could be purely hydrogen and electricity based and therefore potentially emission free. Energy demand in DRI steel production is approximately 10 GJ/t_{CS} and temperature levels reach 3,500° C in the EAF, which is the most energy-intensive production step.

The main challenge for deep decarbonization of European steel production is to reduce emissions from the energy and emission intensive primary route. This entails reducing both energy and process related emissions. Technologically, deep emission abatement in steel production is possible and studies have shown different transformation scenarios [5, 44–46]. In addition to the economic challenges associated with such a transition, further challenges result from long technology lifetimes of blast furnaces of 50 years or more, with major refurbishment cycles due every 20 years [5]. Fifty percent of European blast furnaces will require significant investment until 2030. The remaining 50 % of primary production capacities are due for refurbishment between 2030 and 2040. To minimize the costs for stranded steel production assets, investments into green steel production technologies should occur at the end-of-life of the incumbent technology or when major refurbishments become necessary. In this context, half of Europe's primary steel production capacity has only one opportunity for reinvestment until 2050 while the other half has two.[23]

Chemicals and Petrochemicals

The **chemical and petrochemical** industry branch, as reported by Eurostat, encompasses the NACE categories 20 and 21. EU27+3 gross value added in this industry branch was € 274 bn or 10 % of total GVA

[22] Specific energy demand is mainly influenced by the share of steel scrap added to the charge of the blast furnace. Based on [42] the average estimated scrap share added to Europe's blast furnaces is 8 %. In Hungary it was ~18 % in 2017. Italy's only primary production site in Taranto did not add scrap to the blast furnace according to the calculation based on this source.

[23] [2] shows that the costs for stranded assets in the steel industry in a European net-zero transformation scenario are relatively low compared to total transformation costs. Nevertheless, steel producers are exposed to global competition in a price sensitive market. Additional costs are consequently a risk for global competitiveness.

in 2017 [31]. In SmInd EU the production of high value chemicals (HVC), ammonia, chlorine and methanol are modeled bottom-up (NACE rev. 2 group 20). In total, these processes constitute ~44 % (~102 MT_{CO2}) of the CO_2 emissions in this industry branch. In addition to these energy-intensive processes, further parts of the chemical and petrochemical industry are addressed by cross-sectional measures (cf. section 3.3). Through these measures the transformation of steam production is addressed, which poses another relevant energy consumer in the chemical industry.[24] Table 3 shows key data for the modeled processes.

Table 3: EU27+3 overview for selected basic chemicals for 2017[25]

Product	Number of sites	Production tonnage	Avg. feedstock demand	Avg. energy demand	Direct CO_2 emissions	Indirect CO_2 emissions
	#	Mt	$GJ/t_{product}$	$GJ/t_{product}$	Mt_{CO2}	Mt_{CO2}
Ethylene	44	20	43	38	40	3.8
Aromatics		9.3		8.0	3.7	0.98
Ammonia	35	18	21	14	28	13
Methanol	6	2.4	23	13	4.3	0.2
Chlorine	66	9.6	-	13	0.5	8.5

HVC are produced in 44 steamcrackers across Europe [47]. This is done by cracking the long-chain hydrocarbons naphtha and LPG to shorter chained HVC at ~850 °C [51]. HVC can be categorized as olefines (i.e., ethylene, propylene and C4 streams) and aromatics (i.e., benzene, toluene and xylenes). In SmInd EU olefine and aromatics production are modeled as two separate processes because the climate neutral production pathways for both product categories can differ. For the production of olefines all energy consumed by steamcrackers is attributed to ethylene production, since production tonnage data for other olefines is incomplete for some of the EU27+3 countries [52].

In the EU27+3, 20 Mt of ethylene and 9 Mt of aromatics were produced in 2017. This resulted in ~49 Mt_{CO2} emissions, which originated primarily from energy related fuel consumption during the cracking of naphtha and LPG. The analysis in [51] shows that 25 % of the European steamcracker feedstock is LPG and 75 % is naphtha. Specific feedstock demand is 43 GJ/t_{HVC} [52]. The average energy demand for ethylene is 38 $GJ/t_{ethylene}$. The energy demand attributed to aromatics is 8 $GJ/t_{aromatics}$. Hereof ~95 % and ~85 % respectively, result from fuel consumption. Natural gas and fuel oil are the main energy carriers used for heat provision in steamcrackers [23, 53, 54]. Both are by-products of the cracking process.[26]

For ammonia (NH_3), EU27+3 production totaled ~18 Mt_{NH3} in 2017. Total emissions from ammonia production were ~41 Mt_{CO2}. Hence, specific emissions of European ammonia production were ~2.2 $t_{CO''}/t_{NH3}$.[27] In Europe ammonia is produced at 35 production sites via the Haber-Bosch process [5, 48]. Temperatures reach up to 950 °C during steam reforming of natural gas [51]. The average energy demand is approximately 14 GJ/t_{NH3}, of which approximately 47 % is natural gas and 53 % electricity demand. In addition, ~21 GJ/t_{NH3} of hydrogen feedstock are required for ammonia synthesis. Currently, this hydrogen is produced mainly via natural gas steam reforming. Smaller amounts of hydrogen accrue as a by-product during chlorine production.

[24] The FEC for steam relevant process heat below 500 °C totals ~ 125 TWh of mainly natural gas FEC in 2017.

[25] Industry sites derived from [5, 47–50]. For country-specific data and references for production tonnages, specific consumption, and emissions factors confer appendix 9.3. Ethylene is used as a proxy for the entire olefine production. Refinery crackers not included.

[26] For this analysis it is assumed that natural gas is the only fuel in use. According to [53] the main energy carrier is natural gas and only small amounts of hydrogen and fuel oil are also used energetically.

[27] In [5, 53] specific CO_2 emissions of ammonia production are stated as 2.5 t_{CO2}/t_{NH3}. Own calculations yield ~2.2 t_{CO2}/t_{NH3} because excess heat from ammonia synthesis (4.3 GJ/t_{NH3}) is treated as a heat credit. This heat credit turns into a heat debt in case the process is substituted through alternative ammonia production routes for emission reduction purposes [51].

In the EU27+3 a total of ~2.4 Mt of Methanol (MeOH) was produced at six locations in Norway (1), Germany (4) and the Netherlands (1) [49]. If natural gas is used as a feedstock, MeOH is produced via steam reforming. During this process temperatures of up to 950 °C are reached [51]. In the case of heavy fuel oil feedstock, the main process steps are partial oxidation and the subsequent water-gas shift reaction. Emissions for MeOH production totaled ~4.5 Mt_{CO2} in 2017. Specific emissions of MeOH production are consequently 1.8 t_{CO2}/t_{MeOH}. The energy requirement is ~13 GJ/t_{MeOH}, of which 95 % is fuel demand and 5 % electricity. In Germany, which is responsible for ~40 % of European MeOH production, this fuel demand consists of 60 % heavy fuel oil and 40 % natural gas. Due to the lack of more detailed data, this share is assumed for the entire EU27+3 production volume. Like ammonia production, methanol synthesis requires large amounts of hydrogen (~23 GJ/t_{MeOH}).

Lastly, ~10 Mt of chlorine were produced at 66 different electrolysis sites across the EU27+3 in 2017 [50]. Total emissions amounted to ~9 Mt_{CO2} of which 95 % were indirect emissions from electricity consumption. Specific chlorine production emissions were approximately 0.96 t_{CO2}/t_{Cl}. Since the Europe-wide phase-out of the mercury cell by the end of 2017, only production in the membrane (89 % of total production 2017) and diaphragm cell remain (11 %). Hereby, chlorine production is predominantly electricity based, except for small amounts of steam used in the diaphragm cell. Deep emission cuts are therefore contingent upon emission free electricity production.

The main challenge for deep emission reduction for basic chemicals production is that both emission free energy carriers and feedstocks are required. Depending on the basic chemical transformation pathway, the chemical industry can turn into a significant driver for renewable electricity and hydrogen demand. Some chemical processes also face the challenge of long and urgent reinvestment cycles. For example: the transformation of steamcracker capacities is challenged by technology lifetimes of 50 years or longer for steamcrackers, of which approximately 53 % are pending significant refurbishment until 2030 [5]. This increases the transformation pressure as well as the carbon leakage risk.

Non-metallic Minerals

The **non-metallic minerals** industry branch, as reported by Eurostat, encompasses the NACE category 23. EU27+3 gross value added in this industry branch was € 76.4 bn in 2017, which equates to ~3 % of total GVA [31]. In SmInd EU, the cement (NACE rev. 2 group 23.51) and lime (NACE rev. 2 group 23.52) production processes as well as the flat glass (NACE rev. 2 group 23.11) and container glass (NACE rev. 2 group 23.13) processes are modeled bottom-up. In total, these processes constitute ~78 % (~170 MT_{CO2}) of the CO_2 emissions in the non-metallic minerals industry branch. Processes not covered bottom-up are mainly the manufacture of porcelain, ceramic, clay building materials, special glass and products of concrete, cement and plaster. Table 4 provides key data for the modeled production process.

Table 4: EU27+3 overview for selected non-metallic minerals for 2017[28]

Product	Number of sites	Production tonnage	Average energy demand	Direct CO_2 emissions	Indirect CO_2 emissions
	#	Mt	GJ/$t_{product}$	Mt_{CO2}	Mt_{CO2}
Cement	230	18	3.1	112	7.5
Lime	168	24	4.5	28	0.63
Container glass	164	22	7.2	8.1	3.3
Flat glass	46	10	14	7.8	3.2

[28] Industry sites derived from [39, 40, 55, 56]. For country-specific data and references confer appendix 9.3. Cement sites incl. grinding only sites. Lime sites solely from EU ETS [40] and E-PRTR [39] database. Country-specific clinker-cement-factor used, with an EU27+3 average of ~0.74 [57].

In SmInd EU all cement is treated as Portland composite cement, which typically has a clinker share between 65 % and 94 % [58]. Country-dependent clinker-cement factors are determined based on [59]. Furthermore, the production of cement is linked to the steel and power sector, since slag and fly ash are added as clinker substitutes during cement production.

With 119 Mt_{CO2} emissions to produce 180 Mt of cement in 2017, the cement production process dominates the EU27+3 emissions in the non-metallic minerals industry branch. Average specific emissions of cement production in the EU were consequently ~0.66 t_{CO2}/t_{cement}. In 2017 cement was produced in 230 integrated cement plants spread out across the EU27+3 [55]. The homogenous distribution results from the circumstance that the transport of cement is costly and therefore uncommon [5].

With 112 Mt_{CO2} direct emissions pose the dominant source of emissions in cement production. Hereof 71 Mt_{CO2} are process related, caused by the dissociation of limestone, and 41 Mt_{CO2} are energy related. Of these emissions, 98 % are allocated to the rotary kiln, in which the burning of prepared raw materials to clinker takes place at temperatures of up to 1450 °C [60]. In this process step 85 % of the specific energy demand in cement production (~3.1 GJ/t_{cement}) is located. In the rotary kiln, almost the entire energy demand is met by fuels, of which a high share are so-called alternative fuels (e.g. plastic, municipal waste, tires) [61]. In Germany the average share of alternative fuels reached 65 % in 2017 with approximately one third being industrial biomass such as animal meal, sawdust or sewage sludge [61]. According to [62], today the average use of alternative fuels can reach up to 80 % in European cement production. The variety of fuels viable for combustion during cement production is very high compared to other processes. Fuel substitution is consequently not a new topic for the cement industry. Indirect emissions during cement production predominantly stem from the grinding of raw materials and cement in ball, vertical or material bed roller mills.

Lime production mainly occurs in shaft and rotary kilns in 168 production sites across the EU27+3. In 2017 the production of 23 Mt_{lime} led to 29 Mt_{CO2} emissions and therefore specific emissions of 1.2 t_{CO2}/t_{lime}. Most emissions in lime production are direct emissions (28 Mt_{CO2}) from the burning of lime, of which 64 % are process related. Moreover, 87 % of specific energy demand for lime production (4.5 GJ/t_{lime}) is allocated to the burning of lime, which occurs at temperatures of up to 1200 °C. Natural gas, lignite and hard coal are the main energy carriers. Lime is an important additive for building slag in primary steel production, hence its demand is linked to the development of primary steel production.

The production of flat glass (FG) and container glass (CG) completes the set of bottom-up processes modeled in the non-metallic minerals industry branch. Together, both processes caused 22 Mt_{CO2} emissions in 2017 in the EU27+3. Emissions resulted from the production 21 Mt_{CG} and 10 Mt_{FG} in a total of 210 mainly natural gas fired glass furnaces. Specific emissions in flat glass production (1.1 t_{CO2}/t_{FG}) are consequently higher compared to container glass (0.53 t_{CO2}/t_{CG}). In both processes melting glass is the most energy-intensive production step with 77 % of total FEC in container and 64 % in flat glass production. Process emissions during glass production result from the dissociation of soda and limestone. For flat glass 17 % of total specific emissions are process related. In container glass production this share is ~8 %. The melting of raw materials in glass production occurs at temperatures between 1450 - 1650 °C [63].

The main challenges for deep emission cuts in the non-metallic minerals industry branch are in reducing process related emissions resulting from the dissociation of limestone. This chemical process occurs even if solely climate neutral energy carriers are used to fire shaft or glass furnaces and rotary kilns. Hence, current concepts for deep emission abatement are predominantly focused on carbon capture and sequestration or usage technologies or identifying substitute products. Additional complexity is added to carbon capture solutions due to the decentralized character of cement production, which complicates the introduction of a carbon infrastructure [5]. To the best of the author's knowledge, the age structure of furnaces in the modeled processes is not publicly available. In [5] reinvestment demand in the cement production industry is estimated at 30 % of rotary kiln capacity until 2030. This in turn, poses similar challenges as described for steel and HVC production, since rotary kilns also exhibit long technical lifetimes of ~60 years [5].

Other Industrial Processes

In the EU27+3, the industry branches **food & tobacco** (NACE rev. 2 groups 10 – 12), **paper, pulp & print** (NACE rev. 2 groups 17, 18) and **non-ferrous metals** (NACE rev. 2 groups 24.4, 24.53, 24.54) are responsible for ~236 Mt_{CO2} emissions in 2017. This equates approximately to the total emissions in the chemical and petrochemical industry branch. EU27+3 gross value added in these industry branches was € 416 bn in 2017, which equates to ~15 % of total GVA [31]. In SmInd EU, the production of dairy (NACE rev. 2 group 10.51), paper (NACE rev. 2 group 17.12), mechanical and chemical pulp, recycled paper (NACE rev. 2 group 17.11) as well as primary and secondary aluminum (NACE rev. 2 group 24.42) are modeled bottom-up and cover ~33 % of the emissions in the respective industry branches. Examples of processes not covered bottom-up are the production of milk powder, meat, bread, beer, sugar, sanitary goods, paper stationary, copper, zinc, and casting of non-ferrous metals. Table 5 summarizes production data for the modeled processes.

Table 5: EU27+3 overview for other SmInd EU processes for 2017[29]

Product	Number of sites	Production tonnage	Average energy demand	Direct CO_2 emissions	Indirect CO_2 emissions
		Mt	$GJ/t_{product}$	Mt_{CO2}	Mt_{CO2}
Dairy	>74	45	2.1	3.9	1.9
Paper	~547	96	7.4	19	15
Wood pulp		11	5.6	-	3.6
Chemical pulp		27	15	7.1	0.76
Recycled paper		58	1.6	1.4	5.7
Aluminum	22	3.4	67	8.0	10
Secondary Al	44	3.3	3.8	0.61	0.15

In 2017, 45 Mt of the dairy products drinking milk, cream and acidified milk were produced in the EU27+3. Emissions totaled 5.8 Mt_{CO2} in 2017, which equals 6 % of CO_2 emissions in the food and tobacco industry. Average EU27+3 specific emissions of dairy production are 0.13 t_{CO2}/t_{dairy}. The main energy intensive process steps are pasteurization, homogenization, and ultra-heat treatment. Process temperatures reach their maximum during ultra-heat treatment at ~140 °C [32]. Energy demand for process heat procurement during milk production stems from natural gas based hot water and steam production. One ton of fresh milk product requires 2.1 GJ/t_{milk}, of which ~75 % are fuel and ~25 % are electricity.

The paper production process can be split into three steps: production of primary and secondary (recycled) fibers, production of paper, cardboard and paperboard in the paper machine, and paper surface treatment. SmInd EU covers the production of primary and secondary fibers as well as paper. The post-processing into different types of paper products is not included. Hence, paper is treated as a homogenous good.

In total, 96 Mt of paper and 96 Mt of paper fibers (chemical and wood pulp as well as recovered fibers) were produced at ~547 production sites. Thereby, 22 % of pulp production occurred in integrated paper production sites where both pulp and paper production take place [65]. In this dissertation it is assumed that the entire pulp production is non-integrated. Total emissions from fiber and paper production in 2017 were ~53 Mt_{CO2}, of which 65 % resulted from the paper machine and 35 % from primary and secondary fiber production. Approximately half of the total emissions were indirect emissions. Since both steam and

[29] Industry sites derived from [39, 40, 64]. For dairy, secondary aluminum and paper production, number of sites is based solely on [39, 40]. Hence, only emission intensive sites are included. Validation using external sources was not possible for dairy production, due to the high number of small sites. Validation of paper production sites using high-level aggregated data in [65] shows that site number is plausible. For country-specific data and references confer appendix 9.3.

electricity are required in paper production combined heat and power (CHP) plants were a common heat and electricity source.

The modeled paper production processes cover 78 % of the industry branch emissions. Specific emissions of paper production in the EU27+3 vary by country, since the respective biomass share in paper production ranges from no biomass at all in Italy to 89 % in Sweden [66]. Besides biomass, the main energy carriers deployed are natural gas and coal. European average emissions for fiber production were 0.19 t_{CO2}/t_{fiber} and 0.36 t_{CO2}/t_{paper} for the paper machine. Paper production in the paper machine demands 7.4 GJ/t_{paper}, chemical pulp production 15 GJ/t_{pulp}, wood pulp production 5.6 GJ/t_{pulp} and fiber recovery 1.6 GJ/t of recycled paper.[30] The main fuel consumer in paper production is the thermal drying of fiber suspension using steam in drying cylinders at ~100 °C in the paper machine. During chemical pulping, 50 % of FEC is allocated to dewatering and drying of fibers. The highest temperatures of 160 – 180 °C are reached during the cooking of chemicals and woodchips [67]. Since 98 % of FEC in this step is fuel based, it is also the dominant fuel consumer in chemical pulp production. Mechanical pulping is mainly electricity based. Its production causes waste heat which can be recovered in the form of hot water and steam.

In 2017 3.4 Mt of primary aluminum was produced at 22 production sites across the EU27+3. Hereof the bulk share of 38 % was produced in seven primary sites in Norway. Total emissions for primary aluminum production were 18 Mt_{CO2} in 2017. Average specific primary aluminum emissions in the EU27+3 were consequently 5.3 t_{CO2}/t_{Al}. Of this, 30 % were process related emissions mainly resulting from the anode burn-off [68]. The former describes the effect by which the carbon anode is depleted during cell operation. This is caused by a reaction of the positively charged anode with oxygen anions, thereby forming CO and CO_2 in an exogenous reaction. With 67 GJ/t_{Al} the primary aluminum process poses the highest specific energy consumption of all bottom-up processes covered in SmInd EU, with 81 % coming from electrical energy demand. Aluminum electrolysis is the most energy-intensive process step, which is solely powered by electricity with 53 GJ_{el}/t_{Al}. Specific aluminum emissions therefore depend heavily on the emission factor of electricity, leading to large differences amongst countries. During aluminum electrolysis cell temperatures reach 950 °C [68].

In addition to primary aluminum, 3.3 Mt of secondary aluminum were produced at 44 sites, leading to 0.76 Mt_{CO2} emissions. In comparison to primary aluminum, specific emissions (0.23 t_{CO2}/t_{Al}) and energy demand (3.8 GJ_{el}/t_{Al}) of secondary aluminum production are low.[31] Moreover, process emissions resulting from scrap impurities during melting are negligible. During secondary production the maximum temperature of ~660 °C is reached during aluminum melting [68].

The main deep emission reduction challenge for low-temperature processes such as dairy and paper production is the emission-free provision of hot water and steam for the procurement of process heat. Low-temperature processes are at an advantage compared to high-temperature processes such as steel or cement production, since the source of hot water and steam production does not affect the respective production processes [37]. In aluminum production, process emissions resulting from the anode effect pose a challenge to deep emission reduction. Energy-related emissions currently result mainly from electricity consumption, which does not pose an immediate challenge to the industrial actor.

Preliminary Summary

In the previous sections, the cornerstones of the most energy and emission intensive processes in the European industry sector were described. Figure 9 summarizes aspects highlighting the main emission reduction challenges for each of the modeled processes.

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[30] For specific fuel consumption in chemical pulping the average of the sulfite (3056 kWh/t_{pulp}) and sulfate (4167 kWh/t_{pulp}) processes is assumed. Both processes exhibit the same electricity demand (639 kWh/t_{pulp}) [67]. For mechanical pulping the specific energy demand for groundwood pulp is used.

[31] The energy demand varies depending on scrap impurities. For further details confer [68].

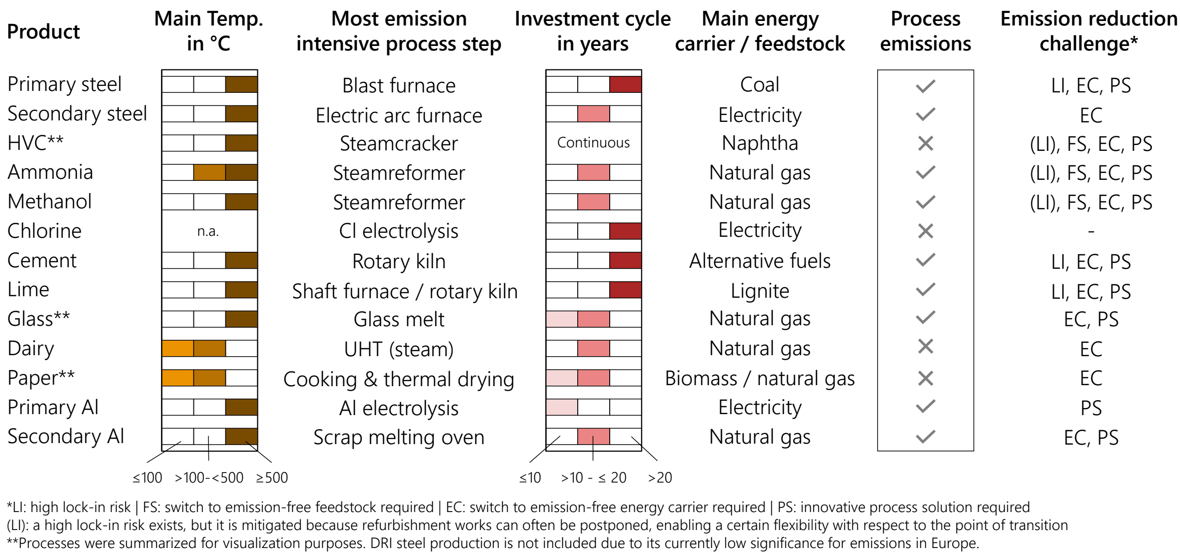

Figure 9: Overview of key challenges for emission reduction in SmInd EU processes

For the listed energy-intensive products the figure shows production process characteristics which impact the difficulty of achieving deep emission cuts by 2050:

- The **main process temperature** and **most emission-intensive process step/technology** serve as indicators for the complexity of the technological solution required to achieve deep emission reduction. In general, higher process temperatures required for smelting, melting and other heat treatments are produced with specialized appliances such as furnaces and kilns. On the other hand, lower process temperatures occur when there is a demand for hot water and steam. The latter are produced with non-process-specific technologies such as gas boilers. Hence, with higher process temperatures the emission reduction challenge increases due to added technological complexity.
- The length of the **investment cycle** indicates the number of potential chances for re-investment in production technologies until 2050.[32] The longer the investment cycle, the less chance for re-investment without the risk of stranded assets until 2050. This criterion therefore serves as an indicator for the risk of potential lock-in effects and path dependencies during the transformation up to 2050.
- The **main process energy carrier/feedstock** provides an indication for the need of a fuel switch to achieve deep emission cuts up to 2050. For processes currently powered by fossil fuels, the industrial actor faces the challenge of finding an emission-free alternative. If electricity is the main energy carrier, this challenge is passed on to the energy supply-side.
- If **process emissions** exist, additional complexity is added to the emission reduction challenge, since not only energy procurement but also chemical reactions within the production processes cause CO_2 emissions. In most cases this increases the need for process-specific solutions (e.g., steel, aluminum).

Figure 9 highlights that especially steel, cement, lime, glass, basic chemicals, and aluminum production demand process-specific solutions to achieve deep emission cuts. Except for aluminum electrolysis cells these processes face the risk of lock-in effects since technology lifetimes and major refurbishment cycles frequently exceed 20 years. This leaves one to two opportunities for process substitutions until 2050. Moreover, industrial actors face both the challenge of switching to carbon natural energy carriers and

[32] Except for steel and HVC the age structure of appliances across Europe is unknown. Hence the investment cycles are used as indicators for the theoretical number of possible technology exchanges until 2050.

feedstock as well as reducing process emissions. In the following section, the process for identifying, selecting, and quantifying greenhouse gas abatement measures is described.

3.3 Industrial CO_2 Abatement Measures

Based on the information about the structure of industrial energy consumption and emissions, technical CO_2 abatement measures for the European industry sector are classified (cf. section 3.3.1), identified and selected (section 3.3.2), as well as parametrized (section 3.3.3). Ultimately an overview of the emission abatement potential of the quantified measures is provided in section 3.3.4.

3.3.1 Emission Abatement Strategies

To support the structured identification of individual technical abatement measures, the main strategies for industrial emission abatement are summarized below.

- Energy and material efficiency: reducing the material and energy input at constant output
- Fuel and material substitution: substituting fossil fuels and emission intensive materials through climate friendly alternatives
- Carbon capture: capturing emissions at the point of origin
- Energy and material sufficiency: reducing energy and material use by lowering the output

As shown in Figure 10, the four main strategies can be sub-divided into more specific abatement strategies.

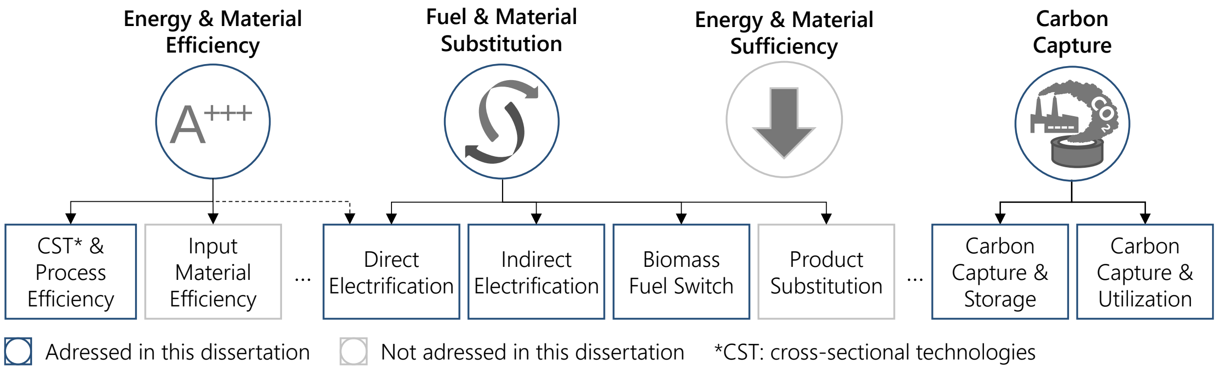

Figure 10: Industrial CO_2 abatement strategies and relevance for this dissertation[33]

Since achieving deep emission reduction in the industry sector requires the mitigation of direct, indirect and process emissions a combination of strategies is required to reach climate targets [1]. In the following, key aspects for each strategy including the main advantages and disadvantages are discussed. Furthermore, the meta-analysis of energy politic studies in Germany in [1], conducted by this author, is used to identify the role each abatement strategy assumes in deep emission reduction scenarios. In this analysis seven energy political studies encompassing 17 scenarios are evaluated with focus on industrial transformation pathways.[34] Based on this analysis of advantages, disadvantages, and the role of each abatement strategy, implementation guidelines for the scenario process in section 5.2 are derived.

[33] Based on [69] the measure category *Energy & Material Sufficiency* is excluded, due to the assumption that growth will remain the dominant paradigm in the industry sector. Modeling material streams and product usage are out of scope of this thesis. Hence, material efficiency and product substitution are not considered. Furthermore, circular economy measures are not classified as technical abatement measures, but as facilitators for increasing secondary steel or aluminum production.

[34] The published analysis was expanded to include the most recent scenario study for Germany [70] as well as the European (industrial) mitigation scenarios [4, 52].

Efficiency – CST & HW & Process Efficiency

Increasing energy efficiency of CST & HW and industrial production processes alone is insufficient for achieving deep emission reduction in the industry sector. This results from lower physical boundaries of energy consumption in production processes as well as the fact that process emissions are not affected by efficiency measures [71]. Nevertheless, the meta-analysis in [1] shows that efficiency measures are a prerequisite for a successful industrial energy transition. Hereby, the long-term role of efficiency measures is to limit the demand for scarce emission free energy carriers such as electricity, biomass, or synthetic fuels. In the short and medium-term, efficiency measure implementation aids the achievement of intermediate milestones, such as the 2030 climate targets. With respect to the scenario construction process in section 5.2, the efficiency-first principle is followed, and efficiency measures are treated as no-regret measures.

Fuel Substitution - Direct and Indirect Electrification

Electrification technologies can be categorized as direct or indirect electrification measures. Direct Electrification is defined as "replacing (…) fossil-fueled end-use technologies (existing or planned) with more efficient electric end-use technologies." [72, p. vii]. Indirect Electrification is defined as *the substitution of fossil fuels through electricity-based hydrogen and synthetic fuels or gas* [73]. Given that the electricity supply is emission-free, electrification measures can facilitate deep energy-related emission reduction.[35] In addition, depending on the respective industrial process, electrification measures can also facilitate the reduction of process emissions. The meta-analysis in [1] shows that electrification is a prerequisite for deep emission reduction in the industry sector. The degree to which direct and indirect measures are implemented varies significantly across the analyzed scenarios, thereby reflecting the high degree of uncertainty associated with innovative process solutions. Due to this uncertainty further analyses are performed to derive a consistent implementation guideline for electrification measures during scenario construction in section 5.2.

Figure 11 provides an overview of the theoretical electrification potential (TEP) in the EU27+3. Consistent with the definition of the direct electrification potential provided in [37] the theoretical (direct and indirect) electrification potential is defined as *the maximum possible FEC which can be directly or indirectly substituted through electricity and is currently not supplied electrically or through emission-free energy sources (e.g. biomass)*. Figure 11 shows that the EU27+3 TEP amounted to 1738 TWh in 2017. As described in several publications such as [6, 18, 37, 69, 74, 75], both direct and indirect electrification solutions exist for several industrial production processes and temperature levels. Thereby, independent of the temperature level, efficiency gains from direct electrification outweigh those from indirect electrification [75]. Hence, the so-called *electrification decarbonization efficiency* of direct electrification measures exceeds that of indirect electrification measures [18].[36] This results from conversion losses during the production of hydrogen and synthetic fuels [73]. To minimize the additional demand for emission free electricity, direct electrification measures should therefore be prioritized over indirect measures in situations where both are viable options. The availability of direct electrification solutions at industrial production scale is hereby influenced by the process temperature level.

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[35] As stated in [53] hydrogen can also be produced from methane pyrolysis. The technology readiness level of this production route is lower compared to electrolytic hydrogen. Nevertheless, this technology could be another source of emission-free H_2.

[36] The latter is defined as the additional electricity demand per mitigated ton of CO_2 [18].

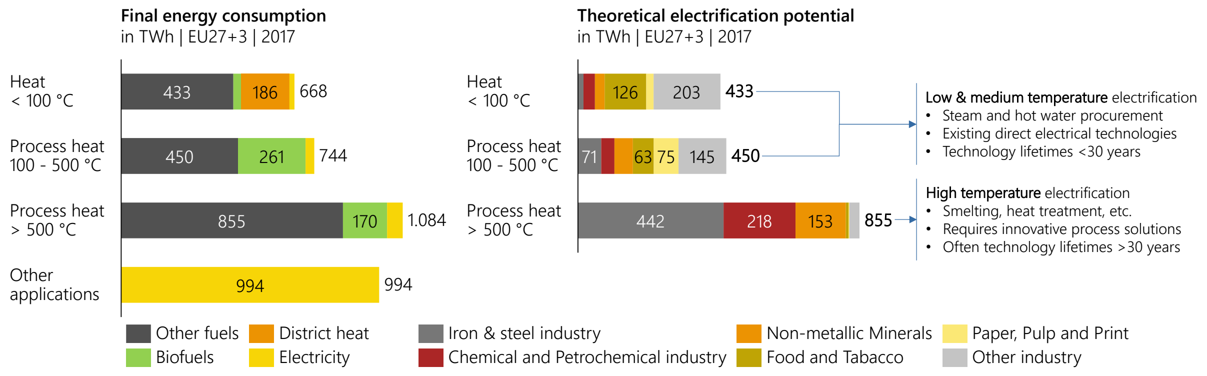

Figure 11: FEC and theoretical industrial electrification potential for the EU27+3, 2017[37]

The so-called low-hanging fruits of direct electrification are the electrical procurement of hot water and steam. These substitution processes are characterized by low technical complexity. Moreover, market ready electrical technologies exist for these applications (e.g. industrial heat pumps) [37, 76]. The substitution of low-temperature fossil heating appliances through industrial heat pumps, for example, results in much improved efficiency [37]. For low- to medium-temperature applications indirect electrification measures pose a viable yet less efficient solution [77].

The analyses in [75, 78] show that process temperatures as high as 5,000 °C can be achieved with direct electrical technologies (i.e. plasma beams). Nevertheless, high-temperature processes require process-specific solutions. In practice, direct electrical production routes for steel, glass, and non-ferrous metal production have been demonstrated or are state-of-the-art. The corresponding technologies are electric arc furnaces, electric glass furnaces and inductive as well as conductive electrical casting furnaces (e.g. for copper and aluminum) [69]. Even though high temperature levels can be achieved with electrical technologies, direct electrification solutions for other energy-intensive high-temperature processes such as cement, ammonia, methanol or HVC production have yet to be demonstrated at industrial scale [69, 79]. These "blind-spots" of direct electrification pose suitable application areas for indirect electrification solutions. The latter include the substitution of fossil energy carriers through synthetic alternatives, the direct combustion of hydrogen in hydrogen burners as well as process specific technological solutions such as hydrogen-based DRI steel production [5, 75, 77]. Furthermore, the use of hydrogen as both energy carrier and feedstock for chemical processes is discussed for a variety of production processes such as ammonia and methanol [5, 75].

While efficiency poses a central decision criterion in favor of direct electrification technologies further opportunities and challenges of both options are summarized in Table 6.

Table 6: Opportunities and challenges of electrification

Potential Advantages	Potential Disadvantages
- Deep emission reductions - Reduced import dependency from fossil fuels - Increased flexibility for the electricity market - H_2 & Electricity: reduction of local emissions - Electricity: increased controllability - Synfuels: low technical complexity for industry	- Increasing demand for emission-free electricity - Additional or new transport infrastructure necessary (e.g., transmission lines, H_2-backbone) - Additional costs to actors and system - No guarantee of process emission reduction

Electrification in general pose the potential advantage of reducing the import dependency of fossil fuels. Furthermore, the hybridization of industrial production technologies and the production of hydrogen via

[37] District heat is not included in the theoretical electrification potential since „(…) it is mainly supplied by vertically integrated companies responsible for the production and distribution (…)." [37, p. 5].

electrolysis are an opportunity for improved integration of variable renewable energy sources [75, 78]. Both the use of hydrogen and electricity to procure heat reduces local emissions. Furthermore, from the perspective of the industrial actor, the use of synthetic fuels as a chemically equivalent substitute for fossil energy carriers minimizes the technical transformation complexity, since existing heating appliances can be used. Lastly, direct heating technologies can increase the controllability of process heat procurement, thereby reducing losses [75].

By contrast, electrification increases the decarbonization challenge on the supply-side [6, 69]. The analyses in [6, 80] show that high direct electrification rates can result in significant challenges for the expansion of vRES as well as the transmission network, leading to additional system costs (cf. section 7.3). Indirect electrification drives the demand for emission-free electricity as well. Moreover, additional and new transport infrastructure demands arise (e.g., transmission lines, H_2-backbone). Ultimately, despite the high emission reduction potential of direct electrification solutions, the reduction of process emissions is not guaranteed. For instance: the electrical production of steel, flat and container glass does not eliminate process related emissions [69].

Despite the challenges associated with electrification measures, deep decarbonization in the industry sector requires the implementation of such measures. For scenario construction in section 5.2 direct electrification measures are prioritized over indirect electrification measures due to their efficiency advantage. In case indirect electrification is required to facilitate deep emissions reduction, the direct use of hydrogen is the most preferred of hydrogen derivatives since efficiency decreases with each further processing step.

Fuel Substitution - Biomass

The substitution of fossil fuels through sustainable biomass can facilitate deep emission reduction. The meta-analysis of industrial climate protection scenarios in [1] shows that intersectoral shifts of biomass from households and transport to the industry sector are a common element in industrial emission reduction scenarios. As shown recently in [5, 52], the combination of biomass and carbon capture and storage (BECCS) can lead to negative emissions in certain processes (e.g. cement). However, the potential of sustainable biomass in Europe is limited and controversial. Furthermore, the use of cultivatable land to produce biomass for energy use has been subject to acceptance issues [5]. For scenario construction in this dissertation the use of biomass is consequently restricted to application areas in which no other alternatives for deep emission reduction exist.

Carbon Capture - Storage or Utilization

The carbon capture strategy in Figure 10 encompasses measures leading to the storage or further utilization of carbon. Independent of the respective storage or usage, CC measures can potentially mitigate direct energy and process related emissions. CC is mainly discussed as a mitigation strategy for large industrial emission point sources, with high concentrations of CO_2 in the process exhaust gas [1]. Thereby, the degree to which CC reduces emissions depends on the CO_2 concentration in the process exhaust gas. Examples for abatement rates of CC technologies in steel and cement production are 33 % and 80 % respectively [81]. Large point sources are more suitable for CC compared to smaller ones, since decentralized storage and usage of captured CO_2 results in the demand for an extensive and therefore costly CO_2 transport infrastructure. With respect to these criteria the processes qualifying for the use of CC are limited to steel, lime, cement, ammonia, HVC, and methanol [81].

Despite the ability to facilitate deep emission reduction in these processes, CC technologies face significant acceptance issues [5, 82, 83]. The latter result mainly from worries concerning the unforeseeable effects of long-term storage of CO_2 for ground water and soil as well as the risk of leakages. In line with the implementation guideline for biomass, the use of CC as a mitigation option in section 5.2 is consequently restricted to processes without a viable deep emission reduction alternative.

Preliminary Summary - Emission Abatement Strategies

The summary and analysis of industrial emission abatement strategies shows that a variety of approaches to deep emission reduction exist. Across all energy political scenarios on a German and European level, efficiency measures are considered insufficient but a prerequisite for achieving climate targets. Deep emission reduction can be achieved through fuel substitution measures or carbon capture. The degree to which each strategy is implemented in the analyzed scenarios varies significantly and is driven by sociopolitical, economic, and technical arguments. Amongst the deep emission reduction options especially biomass and CC face acceptance issues. For the processes modeled bottom-up in this dissertation, these measures are therefore considered only in case of a lack of alternatives. Hence, electrification measures are prioritized over biomass and CC options. Amongst the electrification options, direct measures are prioritized over indirect measures due to the higher electrification decarbonization efficiency.

3.3.2 Measure Identification and Selection

The aim of this section is the identification and selection of CO_2 abatement measures, in preparation for their implementation in the industry model SmInd EU (cf. section 4.1). For this purpose, three types of abatement measures are differentiated:

1. Process measures: technology specific measures which address FEC, feedstock consumption and process emissions of the processes modeled bottom-up in this dissertation.
2. Cross-sectional measures (CSM): process and industry branch independent measures which target FEC of certain applications. CSM should not be confused with CST (e.g., lighting, space cooling). While CSM are used to address FEC resulting from CST they also target HW as well as low- and medium-temperature process heat FEC.
3. Proxy efficiency measures: efficiency measures addressing the part of FEC covered top-down (i.e., the part of FEC not linked to a specific technology).

As shown in Figure 12, each measure type addresses different emission categories. Furthermore, process measures and CSM include CO_2 abatement measures from several of the previously introduced abatement strategies (i.e., efficiency, fuel substitution and carbon capture).

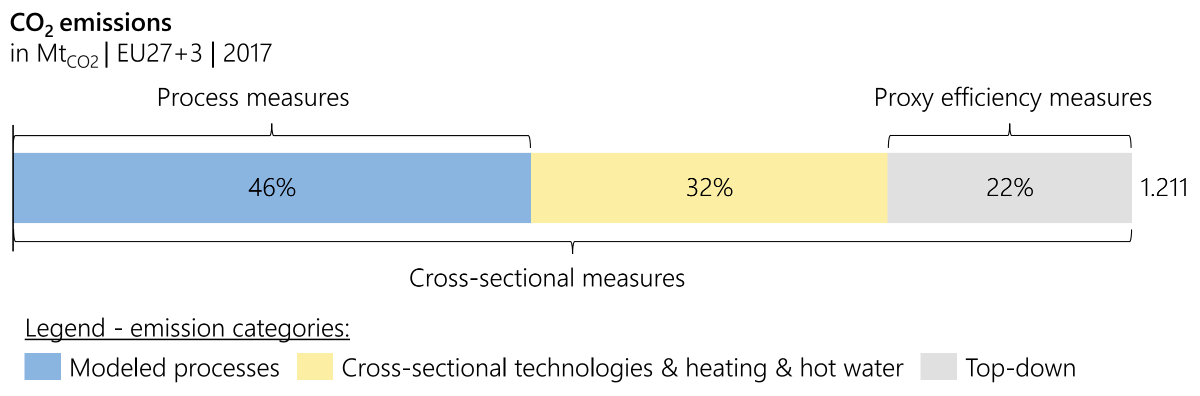

Figure 12: Types of measures and emission categories addressed by measures

The introduced measure types not only address different parts of industrial FEC, but their identification and selection methods differ as well. Figure 13 shows the respective identification and selection methods. Process measures and CSM are technology specific; proxy measures are not.

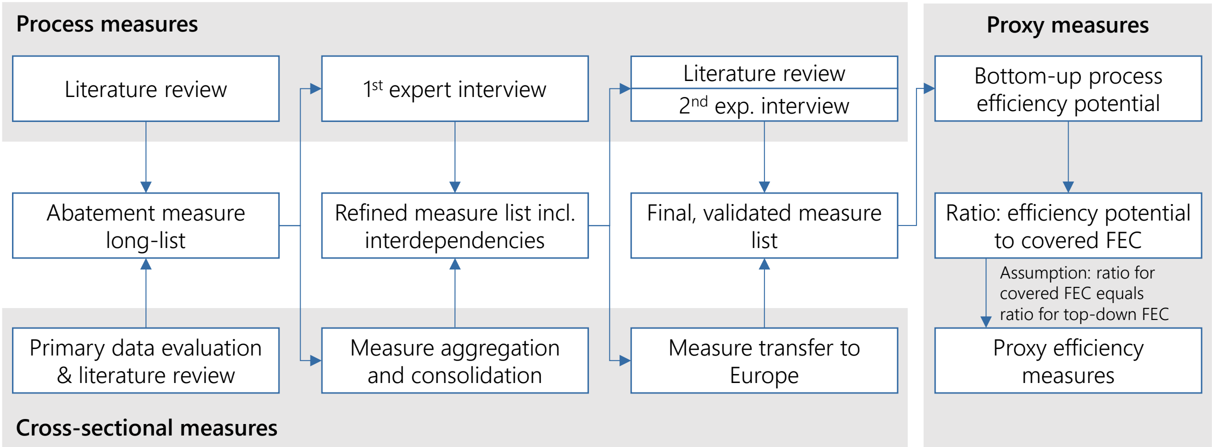

Figure 13: Method overview for the identification and selection of CO_2 abatement measures[38]

As shown in Figure 13, first, a long-list of abatement measures for process measures and CSM is derived. For process measures this long-list includes efficiency, fuel substitution and carbon capture measures. By this means measure identification is constrained to the processes selected for bottom-up modeling in section 3.2. It is based on the review of European and German industry roadmaps, energy political scenario studies and technology reports for each of the processes modeled bottom-up. These measures are process-specific and predominantly treated as country independent. The latter is consistent with the assumption that the main characteristics of industrial processes are country independent (cf. section 3.2). The CSM long-list includes cross-sectional technology efficiency and fuel substitution measures. The initial CST efficiency long-list is derived from real data collected during Learning Energy Efficiency Networks and energy audits operated by FfE [6].[39] This list contains approximately 2,500 identified and evaluated measures from German and Austrian companies across all industry branches and applications. Cross-sectional fuel substitution measures are identified based on literature review.

In step two, the process and CSM long-lists undergo refinement. For process measures experts were consulted in semi-structured interviews to validate the initial measure long-list.[40] During this procedure measures were added, excluded, and adapted based on the respective expert opinions. For CSM the long-list was reduced to 27 CST efficiency and fuel substitution measures. This process included deriving average CST efficiency measures from real measures. Fuel substitution measures (e.g., direct electrification of low-temperature process heat using heat pumps) are based on literature values. Costs of all CSMs were validated and updated using product information sheets containing specific cost data for the respective technologies. During the first refinement stage special attention was paid to measure interdependencies, which are summarized in Figure 14 and explained in the following.

If measures are **enabling**, the implementation of a second measure is only possible after a first measure has been implemented. For example: the state-of-the-art cement measure *use of pre-calciner technology with cyclone preheaters* allows the use of fuels with lower calorific values than fossil fuels in rotary kilns [84].

[38] Over the course of this dissertation project the final list of process measures was expanded several times. Hence, not the entire set of process abatement measures and parameters was subject to the expert consultation-based revision and validation process displayed in the figure. Carbon capture and chemical industry measures as well as process measure cost parameters are literature values. However, literature sources for measure data were selected with care and several of these roadmaps (e.g. [45, 53]), technology reports (e.g. [43, 51]) and studies (e.g. [5, 52]) report data which was validated or provided by industry experts.

[39] The data collected during these audits is confidential and therefore not cited. The author of this dissertation was granted access to this data but was not involved in collecting it.

[40] The interviews were conducted in the scope of the master's thesis [19], which was supervised by the author of this dissertation. A total of eight interview partners were contacted several times to validate process and measure data for cement, lime, glass, steel, paper, pulp, dairy, and aluminum production. Measures for the chemical industry and CC measures are solely literature-based.

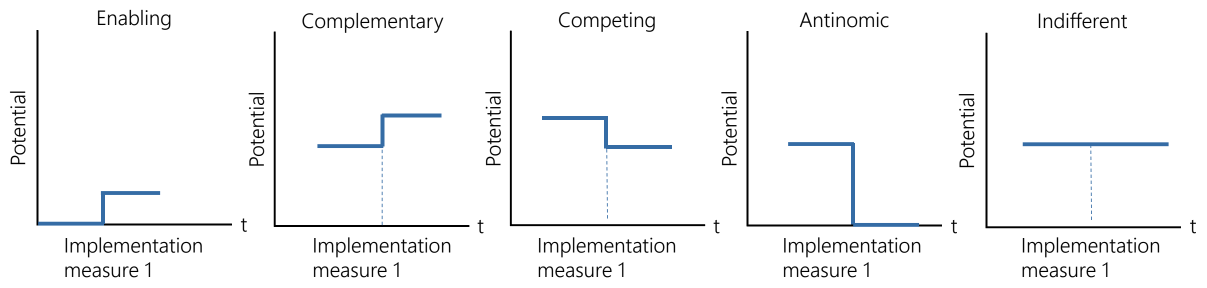

Figure 14: Schematic representation of interdependencies between CO_2 abatement measures[41]

Complementary interactions result if the CO_2 reduction potential of a second measure is increased by the implementation of another. As described in [46, 85] an example of complementary measures is *inert anodes* and *wetted cathodes* in aluminum production. Together these measures are also described as *innovative electrodes*. In current research, inert anodes are the only potentially viable option for eliminating process emissions during primary aluminum production. However, their implementation leads to increased electricity demand during aluminum production. By implementing wetted cathodes, a share of this additional electricity demand is compensated, leading to a complementary measure effect.

Competing interdependencies exist when the implementation of one measure reduces the CO_2 reduction potential of a second measure. This interdependency exists between efficiency and fuel switch measures targeting the same process or application. If the specific energy consumption of a process decreases due to the implementation of an energy efficiency measure, the mitigation effect of fuel switch measures decreases.

Antinomic or mutually exclusive measures cannot be implemented simultaneously. For example, the measures *replacement of ball mills by vertical roller mills* and the *improvement of the grinding medium for ball mills* in cement production are antinomic.

Indifferent measures do not influence each other in terms of the potential to reduce emissions. Both measures can be implemented independently of each other, and potentials can be aggregated.

The different types of measure interdependencies described above are considered during the measure selection phase as well as during the scenario-based measure implementation in section 5.2. Their main goal is to avoid the overestimation of measure potentials and stranded investments during measure implementation. Measure interdependencies can occur amongst measures of the same measure type (e.g., efficiency) as well as between those of different types (e.g., efficiency and fuel substitution). Competing measures of the same type are treated as antinomic measures during measure selection.[42] These interdependencies are technical and occur independently of the scenario at hand. In such cases the measure with the higher specific technical CO_2 abatement potential is selected and becomes part of the final measure list. Costs are not considered as a measure selection criterion but are treated as a result of measure implementation. Interdependencies between measure types are considered during scenario construction since they are scenario dependent. For example: efficiency and fuel switch measures can only compete if both measure types are implemented in the respective scenario. At the end of the treatment of interdependencies stands a refined list of abatement measures.

The refined measure list poses the starting point for the second round of literature research and expert-based validation of process abatement measures and the transfer of CST efficiency measures to other EU27+3 countries. This is done based on the assumption that the energy savings by measure as well

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[41] Own illustration based on [19].

[42] As shown in [38], the high degree of process integration in production processes such as steel, paper, cement, etc. can result in complex measure interdependencies. The latter can lead to partial measure potential constraints (e.g., if measure A is implemented, the potential of measure B is reduced by 10 %). To quantify these partial constraints an analysis of measures at plant level is required, which is not in-scope of this thesis.

as the share of FEC to which these measures can be applied are country independent. The transfer of measure data to other countries is only relevant for CST efficiency measures since they are based on real measure data from German and Austrian companies. Other CSM such as the direct electrification of HW via heat pumps as well as process measures are defined as country-independent.[43] During the second refinement step, the data required for the quantification of measures is validated and finalized.

Ultimately, the finalized list of process efficiency measures poses the starting point for deriving proxy efficiency measures used to model efficiency improvements for the top-down share of emissions and FEC. For this share, technology bound measures cannot be identified and selected. Hence, proxy measures are defined. The technical potential of quantified process efficiency measures is used as an indicator to derive the technical potential for proxy measures, with the underlying assumption that the ratio of technical efficiency potential to FEC is the same for the part of emissions tied to explicit technologies and the top-down share of emissions. Proxy measures are specified for each country and industry branch.

Table 7 provides an overview of the number of measures by measure type and reduction strategy resulting from the identification and selection procedure.

Table 7: Number of selected CO_2 abatement measures by type and strategy[44]

Measure Type \ Strategy	Energy Efficiency	Fuel Substitution	Carbon Capture
Process measures	78	11	2
CSM	24	3	n.a.
Proxy efficiency measures	13	n.a.	

3.3.3 Parametrization of Abatement Measures

Table 8, shows an overview of the technoeconomic parameters used to quantify CO_2 abatement measures in this dissertation. Both the measure type as well as the abatement strategy influence the parameter choice.

Table 8: CO_2 abatement measure parameters by type and strategy

Type \ Strategy	Energy Efficiency	Fuel Substitution			Carbon Capture
		Dir. Electrification	Indir. Electrification	Biomass	
Process	$ses, af, act, l, sCAPEX, sO\&M$	$af, act, ses, l, ecs, sCAPEX, sO\&M$		ecs, l	$af, ar, sc, l, sCAPEX, sO\&M$
CSM		$\eta, af, act, l, sCAPEX, sO\&M$	fec, l		n.a.
Proxy		n.a.			

af: application factor | act: activity figure | ses: specific energy savings | sc: specific consumption | l: lifetime | emf: emissions $sCAPEX$: specific capital expenditure | $sO\&M$: specific operation & maintenance cost | ecs: energy carrier shares $ectas$: energy carrier type application share | η: utilization factor| ar: abatement rate | FEC: final energy consumption

Technical Parameters

As depicted in Table 8, efficiency measures are parametrized using the specific energy savings, application factor, activity figure and measure lifetime [17]. The technical energy savings potential of efficiency measures by country and energy carrier type is derived according to expression (3-4). The technical emission

[43] As stated before, CSM address applications are independent of processes and industry branches. For low-temperature process heat electrification measures technology and cost parameters are not differentiated by country due to their technical similarity.
[44] The measure-pool is the same for each country. Measures can exhibit varying parameters depending on the country.

reduction potential for process measures is determined using expression (3-5). As stated in section 3.3.2 the CO_2 reduction potential is also used as a measure selection criterion in case of competing efficiency measures. The technical potential for efficiency measures is defined w.r.t. 2017.

$$pote_{r,b,p,a,m,t,ect} = ses_{r,b,p,a,m,t,ect} \cdot act \cdot af_{m,t} \tag{3-4}$$

$$potem_{r,b,p,a,m,t,e} = pote_{r,b,p,a,m,t,e} \cdot ecs_{r,b,p,t,ect,e} \cdot emf_{r,t,e} \tag{3-5}$$

$$with\ act \in pt_{r,b,p,t}, c_{r,m,t}\ and\ t = 2017\ and\ ect \in fuel, electricity$$

$pote$: pot. energy savings	ses: specific energy savings	act: activity figure	af: application factor
pt: production tonnage	c: no. of companies	r: region	b: branch
p: process	a: application	m: measure	t: year
ect: energy carrier type	ecs: energy carrier shares	$potem$: pot. em. reduction	emf: emission factor

The ses are measure-specific and differentiated by the energy carrier types fuel and electricity. Specific process energy savings, $ses_{r,b,p,m,ect}$, are expressed as fuel or electricity savings per ton of product. CST energy savings, $ses_{r,a,m,ect}$, are expressed per average company.[45] Specific energy savings are positive if additional FEC is caused. Unlike specific process savings, CST efficiency measures address the energy consumption of an application and are not directly tied to an industry branch and process. For both process and CST measures, the specific emission reduction potential results from scaling ses with the respective emission factor. The af indicates the share of energy consumption to which the ses of a measure applies. The af therefore considers for which share of production tonnages or companies a measure has already been implemented or is technically not feasible. In practice, it is country and measure dependent. Limited data availability however does not allow for a country-specific differentiation. Hence, application factors are assumed constant across countries. Ultimately, the total technical potential of an efficiency measure is derived by scaling the ses and af with an activity figure. For processes, the activity figure is the production tonnage which is specified by country and process. For CSM, this is the number of companies in a country. This activity figure is selected because specific energy savings for CSM are related to the average industry company in each country to avoid having a separate activity figure for each application (e.g., no. of pumps, lights, etc.). The technical CO_2 emission abatement potential by process measure is determined using the same logic as applied to the calculation of emissions for industrial processes. Energy savings are disaggregated from energy carrier type to energy carrier level and scaled with the respective emission factors (cf. expression (3-5)). For CST efficiency measures, the same expression is used, only that energy carrier shares for the respective application are used. The lifetime of efficiency measures is used to model the technology exchange rate of efficiency measures (cf. section 4.1.2).

The share of emissions not covered by bottom-up processes or CST & HW is addressed by proxy efficiency measures. These measures consequently address FEC and emissions resulting from the procurement of process heat in processes for which the technological structure is not disclosed in this thesis. They are derived for each country and industry branch, and for fuel and electricity. The energy savings and abatement potential of these measures are calculated using expressions (3-4) and (3-5).[46] However, ses are derived using an upstream data model. To do so, the technical potential of quantified process efficiency measures is used as an indicator to derive the ses for proxy measures. For industry branches partly covered using bottom-up processes (e.g. for iron and steel), it is assumed that the ratio of technical process efficiency potential to the FEC covered by bottom-up processes equals that of proxy measures in relation to top-down FEC in the respective industry branch (cf. expression (3-6)). The same logic applies for industry branches in which no bottom-up processes and measures are modeled. As shown in expression (3-7), in this case, the ratio of total technical efficiency potential to total bottom-up process FEC across all industry

[45] For CST measures first total energy savings are calculated per country and then divided by the number of industrial companies in the respective country. This is done since measure implementation in SmInd EU requires specific energy savings values.

[46] For proxy-measures the energy carrier shares are adapted slightly to reflect the energy carrier shares in the entire industry branch.

branches is used [17]. For the potential calculation, af and act are set to one since proxy measures are not tied to a specific technology.

$$ses_{r,b,m,ect} = \left(1 - \frac{\sum_{r,b,p,t,ect} fc_{r,b,p,t,ect}}{fc_{r,b,ect,t}}\right) \cdot \sum_{r,b,p,t,ect} pote_{r,b,p,m,t,ect} \tag{3-6}$$

$$ses_{r,b,m,ect} = \left(1 - \frac{\sum_{r,p,t,ect} fc_{r,b,p,t,ect}}{fc_{r,ect,t}}\right) \cdot \sum_{r,p,t,ect} pote_{r,p,m,t,ect} \tag{3-7}$$

$$with\ \mathrm{t} = 2017\ \ and\ \mathrm{ect}\ \in \mathrm{fuel, electricity}$$

$pote$: pot. energy savings; ses: specific energy savings; r: region; b: branch; p: process; m: measure; ect: energy carrier type; t: year

The parametrization of fuel substitution measures is differentiated by measure type and abatement strategy. Direct and indirect electrification measures linked to the substitution of process routes are modeled by a shift in production tonnages (e.g., primary to secondary steel). In these cases, the application factor describes the share of the 2017 production tonnages for which the alternative production route is viable. Hereby process specific constraints such as limited scrap availability for the secondary production of steel and aluminum are considered. The respective process energy and feedstock consumption are derived using expressions (3-1) and (3-2). Total production emissions result from expression (3-3). The technical CO_2 abatement potential is consequently calculated as the difference between emissions caused by the two processes [17]. In case of competing measures during the measure selection phase, the process substitution route with the higher specific reduction potential is selected. Best-case situations are compared, in which emission-free energy carriers are assumed where possible. In addition to process route changes, fuel substitution measures within a process can also be parametrized by shifting process energy carrier shares from fossil to emission free energy carriers. The lifetime of industrial processes as well as the time intervals between capital intensive refurbishments are used to model the implementation of process substitution measures.

Fuel substitution measures are defined as CSM. For direct electrification measures this applies to the applications heating and hot water as well as low- and medium-temperature process heat below 500 °C.[47] The latter are modeled as CSM, as the heat source does not affect the respective production processes [37]. Hence, the respective technologies are parametrized process and industry branch independent, by determining the utilization factor of the new electrical and substituted fossil technologies. Ultimately the potential of these measures is calculated using expression (3-4). However, the specific fuel saving and additional electrical FEC are determined in a model endogenous calculation (cf. section 4.1.2). Based on the assumption that electricity is emission-free, electrification measures can facilitate complete emission reduction in this temperature band.

In addition to direct electrification measures, indirect electrification and biomass fuel substitution measures are also modeled as CSM. These measures address the share of high-temperature (>500 °C) process heat demand not tied to specific technologies.[48] Nevertheless, it must be ensured that these measures are backed by foreseeable technological developments. Based on the information provided in [77, 86, 87] turbines capable of burning up to 95 % H_2 feed-gas already exist today. Hence, it is assumed that the direct combustion of hydrogen can substitute the remaining gaseous fuels as of 2040. Furthermore, the flexible combustion of solid fuels such as coals and biomass in multi-fuel burners is an established technology [86]. Since these measures are calculated model endogenously, they are described in section 4.1. Based on the

[47] This means that emissions and FEC are affected independent of whether or not they are covered by processes modeled bottom-up, CST & HW or top down (cf. Figure 12).

[48] Direct electrical solutions in this temperature band require process specific solutions and are therefore not modeled as CSM. Low- and medium-temperature applications with unknown technology structure are covered by direct electrification measures.

assumption that hydrogen is produced with emission-free electricity and only sustainable biomass or RES waste is used, these CSM fuel switch measures could facilitate complete emission reduction.

Lastly, carbon capture measures are parametrized. The relevant parameters are the process-specific carbon capture rate and the additional fuel and electricity demand resulting from measure implementation [88]. The process lifetime and application factors are used as described for process substitution measures. Additional complexity is added to carbon capture measures due to the interplay between the industry model SmInd EU and the energy system model ISAaR (cf. section 2). In SmInd EU, a process-specific CC potential is defined and communicated to ISAaR. Depending on the overall energy system transformation, the cost optimal usage of CC potential is determined in ISAaR. While the additional energy demand resulting from CC potential usage is balanced in ISAaR, a reverse allocation to SmInd EU is performed for the purpose of this dissertation, since the balancing area is restricted to the industry sector. Technology unspecific carbon capture measures are not considered as the potential of this technology depends on the specific density of CO_2 in the process exhaust gasses.

Cost Parameters

Across all measure types and abatement strategies (cf. Table 7), specific capital expenditure and specific operation and maintenance costs are derived for measures tied to a specific technology. Costs are derived from literature sources and the respective values and sources are shown in appendix 9.5. In addition, costs for proxy measures are derived using the same logic as implemented for the calculation of proxy measure energy savings. For the technology unspecific fuel substitution measures, CAPEX and O&M costs are neglected. This assumption is justified by the analysis in [86], which shows that the CAPEX share of total cost for the required burners is <1 % of total measure costs. Operating expenditures (OPEX) result from the respective changes in energy carrier and feedstock consumption as a result of measure implementation. Further assumptions as well as the cost calculation at measure and transformation pathway level are described in section 6.

3.3.4 Technical Abatement Measure Potentials

In this section the CO_2 abatement potentials of the selected measures are discussed. For the full list of technoeconomic parameters see Appendix 9.5. Figure 15 provides an overview the selected measures including their maximum technical reduction potential. The latter is expressed as a percentage of the emissions addressed by the respective measure (i.e., emissions of the reference process or application). For efficiency measures, which address energy related emissions of processes and CST, the maximum potential is calculated based on 2017 energy and emission data. For all other measure categories, the maximum reduction potential is calculated based on the assumption that energy carriers are emission free. For example, by implementing multi-fuel burners in cement and lime production 34 % of total emissions in cement and lime production could be reduced if emission free energy carriers are used. The remaining emissions are mainly process emissions, which are not addressed through fuel substitution measures.

	CO_2 Abatement Measure	Reference Process / app.	CO_2 emissions 2017		Max. Tech. pot. in %*	TRL	EYoI	Effect on FEC***	
			In Mt_{CO2}	in % of tot.				Electricity	H_2
Efficiency	Process efficiency	Process applications	697	50 %	22 %	9	2021	-	o
Efficiency	CST efficiency	CST applications	386	32 %	24 %	9	2021	-	o
Fuel substitution (Processes)	Electric Arc Furnace	Primary Steel	211	17 %	49 %	9	2021	+	+
Fuel substitution (Processes)	H2-DRI & EAF	Primary Steel	211	17 %	100 %	8-9	2025	+	+
Fuel substitution (Processes)	Methanol-to-Olefins	HVC	44	4 %	100 %	8-9	2025	+	+
Fuel substitution (Processes)	Methanol-to-Aromatics	HVC	4.7	<1 %	100 %	7	2025	+	+
Fuel substitution (Processes)	Electrocracker	HVC	48	4 %	100 %	1-3	2040	+	+
Fuel substitution (Processes)	Power-to-Ammonia	Ammonia	41	3 %	100 %	6-9	2025	+	+
Fuel substitution (Processes)	Power-to-Methanol	Methanol	4.4	<1 %	100 %	8	2025	+	+
Fuel substitution (Processes)	Membrane electrolysis	Chlorine	9.2	<1 %	<1 %	9	2021	o	o
Fuel substitution (Processes)	Multi-fuel & H_2 burners	Cement & lime	147	12 %	34 %	9 & 4	2021 & 2040	o	+
Fuel substitution (Processes)	Electrical container glass	Container glass	11	<1 %	63 %	9	2025	+	o
Fuel substitution (Processes)	Electrical flat glass	Flat glass	11	<1 %	55 %	9	2025	+	o
Fuel substitution (Processes)	Innovative electrodes**	Primary Aluminum	18	<2 %	30 %	4-6	2035	+	o
Fuel sub. CSM	Ind. Heat pump	HW & PH <100 °C	167	14 %	100 %	7	2025	+	o
Fuel sub. CSM	Ind. Heat pump & electrode boiler	PH 100 °C – 500 °C	143	12 %	100 %	8-9	2025	+	o
Fuel sub. CSM	Multi-fuel & H_2 burners	PH > 500°C	340	28 %	100 %	9&4	2021 & 2040	o	+
CC	CCS cement / lime	Cement & lime	147	12 %	90 %	6	2025	+	o

*Maximum technical potential in % with respect to addressed CO_2 in 2017 | **The categorization as a fuel substition measure is abstract but justifiable, since carbon anodes which are consumed during primary aluminum production are replaced with inert anodes | ***+,o,-: increase, not affected, decrease
TRL: Technology readiness level (measures the technological maturity on a scale from 1 (basic research) -9 (market ready)) | EYoI: Earliest year of implementation
FEC: Final energy consumption | CSM: Cross-section measure | CC(S): Carbon capture and Storage | CST: Cross-sectional technology | DRI: Directly reduced iron
EAF: Electric arc furnace | HVC: High value chemicals | HW: Heating and hot water | PH: Process heat

Figure 15: Overview of the selected CO_2 abatement measures[49]

In the following sub-sections further insights about the selected measures are provided. Since describing the 102 technology specific efficiency measures is impractical, aggregated technical potentials are discussed. Fuel substitution and carbon capture measures are described in more detail due to their potentially disruptive influence on the respective production processes.

[49] See previous sections and appendix 9.5 for measure details and references.

Efficiency Measures – Processes and Cross-Sectional Technologies

The results of the potential analysis for efficiency measures are depicted in Figure 16. In total, the technical potential of process, CST and proxy efficiency measures equates to 23 % of 2017 industrial energy-related CO_2 emissions in the EU27+3. Hereby the aggregation of measure potentials is permitted since interdependencies between efficiency measures are considered.

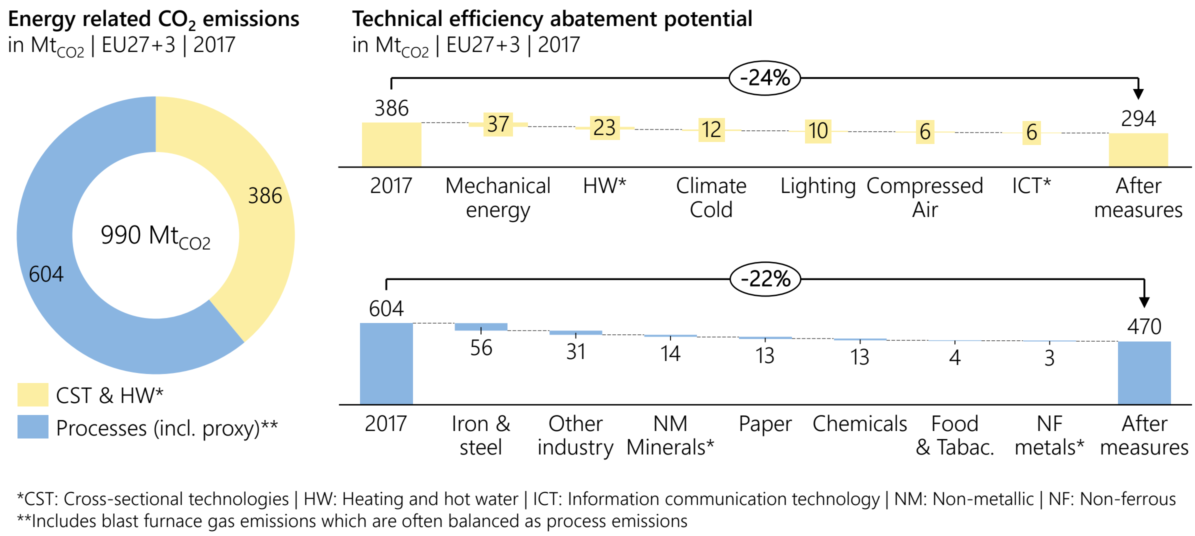

Figure 16: EU27+3 energy-related CO_2 emissions and technical efficiency abatement potential, 2017

Energy efficiency measures in the field of CST can contribute to a 24 % reduction in energy-related emissions in relation to total CST emissions. This equates to a technical reduction potential of 9 % of total industrial energy related CO_2 emissions in 2017. The measures with the highest technical abatement potential are the use of *high-efficiency drives* (14 Mt_{CO2}) and the *control-technical optimization of electric drives* (11 Mt_{CO2}). Both measures address indirect emissions from the mechanical energy application. Hence, the technical measure potential of these measures is directly dependent on the emission factor of electricity, and lower specific electrical emissions result in a reduction of the CST abatement potential.

Process energy efficiency measures can contribute a technical potential for CO_2 reduction of ~135 Mt_{CO2}. This equates to 22 % of the energy-related emissions resulting from process heat applications and 14 % of total energy-related emissions.[50] With 14 Mt_{CO2}, the highest technical potential is attributed to the measure *optimization of the sinter-pellet ratio* in primary steel production [44, 89]. It should be noted that the effect of this measure stands in competition to a potential process route substitution of primary steel towards emission free steel production. Hence, it is possible that in a deep emission reduction scenario the full technical potential of this measure might not be realized despite its high potential.

The potential analysis of efficiency measures for the European industry sector shows that the technical mitigation potential is insufficient for achieving deep emission cuts in the European industry sector. This supports the conclusion derived from the meta-analysis of energy political scenarios which was used to derive the implementation guidelines in section 3.3.1. In the following sections, deep emission reduction possibilities for the modeled processes are introduced.

[50] Due to a higher energy cost share of total production cost in energy-intensive industries, these branches typically exploited more technical efficiency potentials compared to less energy-intensive industries. Since proxy measures are mainly based on technical efficiency measures identified for energy-intensive processes, their potential should therefore be viewed as a lower estimate.

Iron & steel production

The quantification of deep emission reduction measures in the steel industry is based on [5, 43, 44, 46, 52]. The most promising deep decarbonization measures are the expansion of the secondary steel production route in which steel scrap is melted in an electric arc furnace, followed by DRI with hydrogen and subsequent steel production in an electric arc furnace (H_2-DRI & EAF), iron electrolysis, the HIsarna process in combination with CCS and primary steel production in combination with CCU (e.g. Carbon2Chem or Steelanol) [5, 46]. For all mentioned measures emission free energy carriers and feedstock are a prerequisite for deep emission cuts. Table 9 summarizes key data for alternative low-emission steel production routes.

Table 9: Alternative future low-emission steel production routes[51]

Future low-emission steel production route	Technology readiness level	Earliest year of implementation	Specific abatement potential
	#	#	$\%/t_{product}$
EAF	9	2021	98
H_2-DRI & EAF	8 - 9	2025	97
Iron electrolysis	2 – 4	2040 - 2050	87
HIsarna & CCS	4 - 5	2030	86
BF/BOF & CCU	4 - 5	2025	50

Amongst the mentioned measures, secondary steel production presents an established cost as well as an energy efficient and potentially emission-free steel production route. Today, secondary steel production is not emission-free. Emissions stem from the energy carriers electricity and natural gas, the reduction agent coal as well as the electrode burn-off and decarburization of metal. Based on communication with steel-industry experts in [91] the combustion of hydrogen for the procurement of high-temperature process heat as well as the use of hydrogen as a reduction agent will be possible in future. Furthermore, biogenic coal or synthetic methane could substitute fossil coal and natural gas, respectively. Hence, if energy carriers are emission free, secondary steel could be almost emission free except for the comparatively low specific process emissions. However, the limited availability of steel scrap imposes an upper limit to the implementation of this production route. Based on [45, 91] the European limit for secondary steel production until 2050 is estimated at 50 % of the crude steel production in 2017.[52]

Since the substitution of primary through secondary steel production is limited, further measures are required for the deep decarbonization of the European steel industry (cf. Table 9). Based on the data in Table 9 the H_2-DRI & EAF route poses the most promising deep emission reduction option for several reasons. First, existing (pilot) plants in Sweden and Germany show that the production of DRI is technically possible. Under optimal conditions the technical availability at industrial scale is expected as of 2025 [5]. Compared to the other listed emission reduction options the DRI route is associated with the lowest technological uncertainty. Second, it is expected that DRI plants can operate with CH_4 and H_2 as reduction agents without technical adaptations. The successive ramp-up of the (green) H_2-share for DRI production is therefore technically possible. Furthermore, DRI can substitute iron ore in existing blast furnaces. Hence, DRI plants can function both as a bridging and deep decarbonization technology. Third, the specific emission reduction potential of iron electrolysis, HIsarna & CCS as well as BF/BOF & CCU is lower compared to H_2-DRI & EAF (cf. Table 9). Based on these arguments as well as the implementation guidelines in section 3.3.1, the secondary steel production and H_2-DRI & EAF processes are selected as deep emission reduction measures for steel production.

[51] Own table with data from [5, 43, 90].

[52] For Germany this share is limited to 33 %. Experts estimate that scrap availability will limit the substitution potential of the secondary production route for high quality steel currently produced in the primary route [91].

Chemical industry – Ammonia, Olefines, Aromatics, Methanol and Chlorine

The quantification of deep emission reduction measures for the selected chemical processes is based on chemical industry roadmaps and technology reports [5, 46, 51, 53].

Considering the general measure implementation principles laid out in section 3.3.1, currently two viable technology pathways for HVC production exist: the methanol-based processes methanol-to-olefines (MTO) and methanol-to-aromatics (MTA) as well as electrical steamcrackers (E-HVC). Conventional steamcrackers in combination with carbon capture and storage/usage technology are excluded from the list of CO_2 abatement options due to low abatement shares as a result of low CO_2 densities in the exhaust gas [90]. Furthermore, bionaphtha and bioethylene (via bioethanol as feedstock) are excluded since non-bio alternatives exist. Table 10 summarizes key data about these alternative process routes.

Table 10: Alternative future low emission HVC production routes[53]

Potentially emission free production route	Technology readiness level	Earliest year of implementation	Specific abatement potential
	#	#	$\%/t_{product}$
MTO	8 - 9	2025	100
MTA	7	2025	
E-HVC	4 - 5	2040	100

The mentioned process routes only lead to deep emission cuts if green methanol and naphtha are used as process feedstocks. It is possible to produce green synthetic naphtha via Fischer-Tropsch-synthesis [53]. Also, MeOH production can be rid of emissions (see below). All three green process routes are selected, due to the low technology readiness level and the resulting late implementation window for E-HVC.

Technology options for emission-free NH_3 production are limited to the power-to-ammonia ($P2NH_3$) process [5, 52, 53]. Hereby, the required educts for NH_3 synthesis, hydrogen, and nitrogen, need to be procured emission free. This is possible via water electrolysis and air separation, respectively. Both process steps are fully powered by electricity, making the emission abatement potential of $P2NH_3$ fully dependent on the electricity mix. Air separation units for the procurement of nitrogen are an established technology. Commercial availability of industrial scale water electrolysis is expected by 2025 [5].

In general, three potentially climate neutral pathways for MeOH production exist [51, 53]:

1. Power-to-MeOH (P2MeOH): this route is based on (green) H_2 production via water electrolysis and subsequent synthesis of H_2 and CO_2 to produce MeOH. The water electrolysis replaces the reforming step in conventional MeOH generation. Hence, an external climate neutral CO_2 source, such as direct air capture (DAC), is required for MeOH synthesis.
2. Methanol via methane pyrolysis: the alternative methane based MeOH production route builds on hydrogen production via methane pyrolysis. Hereby methane molecules are split into carbon and hydrogen in a non-catalytic high-temperature process. If emission free electricity is used for heat procurement, then this poses a potentially emission free H_2 production route.[54] However, similar to P2MeOH, an additional carbon source is required in this case (e.g., DAC). In addition to a clean energy source, solutions for the reduction of emissions from methane which is not converted during pyrolysis are required. Concepts for such solutions exist, but further research and development (R&D) is required and only possible once methane pyrolysis is fully developed.

[53] Own table with data from [5, 46, 53, 91].

[54] Parts of the methane used as feedstock could be burnt to provide energy. This in turn would result in energy related emissions. Biomethane or green synthetic methane could be used as an alternative feedstock.

3. Biomethanol: MeOH can be produced via the gasification of biomass feedstock. The resulting syngas is then cleansed and the hydrogen to carbon monoxide ratio optimized for MeOH synthesis via a water-gas shift reaction.

Table 11 shows a summary of technical data for the three MeOH production routes. Based on the arguments laid out in section 3.3.1, the hydrogen based MeOH production route is selected for further modeling in the industry model SmInd EU.

Table 11: Alternative future low-emission methanol production routes[55]

Potentially emission free production route	Technology readiness level	Earliest year of implementation	Specific abatement potential
	#	#	$\%/t_{product}$
P2MeOH	8	2025	100
Methane pyrolysis	4-5	2040	97
Biomethanol	6-7	2030	70

Chlorine production is already predominantly electricity based today. While efficiency improvements for this process are included in the analysis, disruptive developments are not required to achieve deep emission reduction in chlorine production.

Non-metallic minerals – Cement, Lime, Container Glass and Flat Glass

The quantification of deep emission reduction measures for the modeled processes in the non-metallic minerals industry is based on [5, 6, 37, 60, 63, 88, 92–95]. As explained in section 3.2 emission reduction in all processes is challenged by the existence of process emissions.

The cement and lime production process are high-temperature processes. ~60 % of the specific emissions in lime and cement production are process related. Discussions about direct electrification measures are gaining trajectory as this thesis is authored [5]. However, to the best of the author's knowledge, data required to quantify such measures is still unavailable and electrical rotary kilns and shaft furnaces still require extensive research and development [62, 95]. Moreover, electrification cannot mitigate the mentioned process emissions from the dissociation of limestone. The direct electrification route for cement and lime production is consequently not considered in this thesis.

As shown in [86, 95] both rotary kilns and shaft furnaces used in cement and lime production can be equipped with multi-fuel burners. The latter already exist today and allow the flexible combustion of a variety of different solid, liquid, and gaseous fuels. In Germany, the share of rotary kilns with multi-fuel burners in cement production is approximately two thirds of total cement production ovens [96, 97]. Approximately one fourth of European shaft furnaces used for lime production are mixed-feed shaft kilns [95]. Compared to other industries, the fuel flexibility in cement and lime production has consequently been very high. If challenges concerning flame properties and the burning of low-calorific biomass are overcome, both processes could function purely based on biomass and RES waste in future [94, 95]. Consistent with the assumption concerning the combustion of hydrogen in secondary and DRI steel production, it is also assumed that currently natural gas fired kilns and furnaces could be operated with pure hydrogen burners. In both production processes energy-related emissions can consequently be eliminated through fuel substitution measures which enable the combustion of synthetic methane, hydrogen, biomass, or RES waster instead of non-RES waste, coal, natural gas, and other fossil-fuels.

Process related emissions in cement and lime production cannot be eliminated by energy carrier substitutions. The dissociation of limestone is a chemical reaction which occurs independent of the energy

[55] Own table with data from [51, 53]. In [53] the earliest year of implementation for industrial scale hydrogen production via electrolysis is assumed in 2030. Accordingly, the earliest year of implementation for P2MeOH is also 2030. The more recent studies [5, 90] show that optimal technology development can lead to market readiness in 2025.

carriers used to provide process heat [60]. Hence, as stated by [5, 92], carbon capture measures are required to achieve deep emission reduction for cement and lime production.[56] For both lime and cement production post-combustion CC is consequently considered as a deep emission reduction measure.[57] Since transport infrastructure analyses are not in-scope of this thesis, it is assumed that the respective transport and storage facilities are in place. The latter poses a significant challenge to the industrial energy transition in cement and lime production, which, amongst other reasons, results from the high geographical dispersion of cement production sites in Europe. With CC in cement and lime production abatement rates of 90 % can be achieved [93]. In combination with sustainable biomass as an energy carrier to procure process heat, a negative emission balance in cement and lime production is possible [5]. Hence, also biomass fuel substitution is considered a viable CO_2 reduction option in the cement and lime production processes.

For both flat and container glass, the full direct electrification via electrical container and flat glass furnaces is a viable deep emission reduction possibility [37, 63]. While process emissions are not eliminated through direct electrification, ~90 % emission reduction through direct electrification measures are achievable in case electricity is emission-free [63]. CC technologies are a technology option for reducing glass emissions, however, glass furnaces are not considered a large point source of emissions compared to cement and lime. Considering the comparably low share of glass production of total non-metallic mineral emissions in Europe (10 %) and the envisioned target of 95 % emission reduction compared to 1990, no further measures are therefore analyzed for glass production.

Other processes and CSM

Amongst the other processes modeled bottom-up are primary and secondary aluminum production. During primary aluminum production emissions mainly arise from electricity use and anode burn-off. While the challenge for mitigating indirect emissions mainly rests on the transformation of the supply-side, the process emissions from anode burn-off can be reduced by deploying so-called inert anodes. By substituting carbon anodes through anodes made out of materials which are inert to the cell electrolyte (e.g., ceramics) the chemical reaction at the anode is reduced. While this results in the reduction of process emissions it also leads to an increase in electricity demand since the exothermic reaction at the anode no longer occurs. For this reason, inert anodes are frequently discussed as a CO_2 abatement measure in combination with wetted cathodes [85]. The latter allow the reduction of the distance between both electrodes resulting in a lower voltage drop and therefore less electricity demand. Together both measures are called innovative electrodes and currently present the only viable deep emission reduction possibility in primary aluminum electrolysis. CC options are currently not expected to play a significant role due to significant technical obstacles and low direct energy related emissions [98].

Technically, the substitution of primary through secondary aluminum poses another measure to mitigate primary aluminum emissions and significantly lower FEC. However, scrap availability also poses a limiting factor to the expansion of secondary aluminum production. Despite efforts to improve aluminum waste recovery methods, the expected increase in global aluminum demand cannot be covered through recycled aluminum alone [85]. Hence, globally an increase in primary production is expected. Nevertheless, this CO_2 abatement option is selected as a possible measure, despite limited potential.

In addition to the analyzed deep emission reduction options for the processes modeled bottom-up, a variety of processes are addressed through cross-sectional fuel substitution measures. These include the low- and medium-temperature processes paper, chemical pulp, mechanical pulp, recycled paper, and dairy

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[56] The material substitution of clinker through so-called innovative binding agents is another measure which could lead to the reduction of process emissions, by reducing clinker production. However, current predictions are that these new types of binding agents will only be applicable in niche markets and cannot function as a general substitute for Portland cement [5]. Due to this prediction and since material efficiency and substitution measures are not in scope of this thesis, the measure is excluded.

[57] Based on [93] and further expert interviews with the scientific association for the German cement industry (VDZ) during the project [91] a combination of post-combustion and oxy-fuel CCS measures is likely for Germany. However, for this thesis only post-combustion CCS is considered, since carbon capture is modeled as one process in the energy system model ISAaR.

production. In line with the implementation guidelines, process heat in these areas is targeted with direct electrification measures. Hereby, direct electrification of process heat below 100 °C and HW through an industrial ground source heat pump is selected as a measure. In the temperature band between 100 °C and 500 °C a combination of heat pump and electrode boiler is selected [5, 18, 37, 80]. The latter is necessary due to the temperature limit of 160 °C for industrial heat pumps [69]. Both electrification measures are modeled as CSM. Hence, measures are not tailored to the mentioned processes, but address the low- and medium-temperature process heat applications across all industry branches. Hereby electrification only occurs if fossil fuels are displaced and can facilitate the full mitigation of energy-related emissions.

In addition to direct electrification CSM, the use of multi-fuel and hydrogen burners and turbines in CHP plants for process heat procurement are selected as CO_2 abatement measures. If the respective energy carrier feed is emission-free, these burners can lead to the full reduction of energy related emissions. The potential and effect of these burners is calculated model endogenously since, where possible, process specific solutions are implemented first. Biomass is used to substitute the remaining fossil solid fuels in high-temperature heat applications as of 2030. Substitution in medium and low temperature applications commences 2040. Hydrogen substitutes natural gas as of 2040. This substitution occurs in high-temperature applications as well as steam provision in the chemical industry.

3.4 Preliminary Summary

In sections 3.1 to 3.4 the necessary steps to answer the question how technical CO_2 abatement measures for the industry sector can be identified and quantified are described. Each step is part of a method to cope with the heterogeneity of industrial processes which is necessary, to identify the most important levers for CO_2 abatement in the European industry sector. Furthermore, each step required to derive an answer to the research question also provides direct input data for modeling industrial transformation pathways. Consequently, the result of this section is a European data model. It includes country-specific energy and emission data on industry branch and process level as well as CO_2 abatement measure data.

The first part of this data model is the energy carrier and application balance which provides energy and emission data for all industry branches in the EU27+3. This balance is then used to identify the most energy and emission intensive industrial processes. Six industry branches which cover ~80 % of total industrial CO_2 emissions are selected for in-depth analysis. In addition, it enables the analysis of cross-sectional technologies, thereby providing the possibility to define abatement measures addressing these applications. For each of the selected industry branches the balancing of process energy, feedstock consumption and emissions lead to the selection of the most energy and emission intensive processes. This in turn poses another step for coping with the heterogeneity of the sector, and provides direct input for modeling industrial processes in the industry model SmInd EU. Combined, the industry branch and process balances disclose the technology structure behind 78 % of industrial CO_2 emissions.

This information is used for the CO_2 abatement measure identification, selection, parametrization, and quantification process. During these steps, measures are defined which facilitate the modeling of a deep emission reduction pathway for the European industry sector. Measure identification and selection for process measures is supported by an expert-interview-based validation procedure. Measures addressing cross-sectional technologies are defined based on real data collected during energy audits. In addition to the technology bound process and CST measures, proxy and cross-sectional measures are defined to address the 22 % of industrial emissions which are not connected to specific technologies. The definition of abatement measures completes the European industrial data model. The result is a data basis showing the energetic and emission structure of the European industry sector at country, industry branch, process, application, and energy carrier level as well as a pool of 131 abatement measures which can facilitate deep emission reductions.

4 European Industry Model SmInd EU

The aim of SmInd EU is the scenario-based calculation of the spatially and temporally resolved industrial final energy, feedstock consumption and process emissions. The main modules of SmInd EU are structured according to Figure 17.

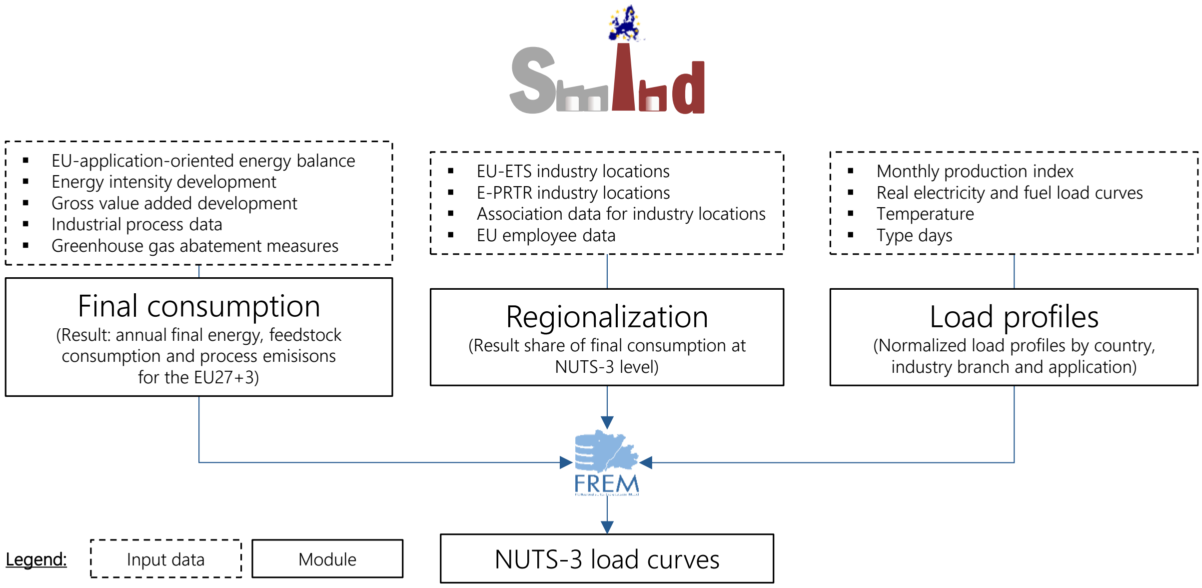

Figure 17: Modular structure of SmInd EU including link to the FREM database[58]

First, annual and country specific industrial final consumption and process emissions are calculated until 2050 (cf. section 4.1). For this step, the industry branch, process, and abatement measure input data described in section 3 is used. Subsequently, the FC and process emissions are regionalized (cf. section 4.2) and then scaled with normalized load profiles (cf. section 4.3), to provide FC time-series in hourly resolution at NUTS-3 level. Data and results of each module are saved in FREM, which is a PostgreSQL database [15].

4.1 Final Consumption Module

The SmInd EU final consumption module is a hybrid bottom-up and top-down MATLAB model. This structure is a result of the necessary trade-off between depicting "… the heterogeneity and complexity of industrial processes whilst achieving full coverage of the …" [17, p. 3], industrial energy, feedstock consumption and process emissions. Changes in FC and process emissions result from the scenario-based implementation of CO_2 abatement measures as well as the development of the macroeconomic metrics gross value added, energy intensity and production tonnages. The FC module is specifically designed to enable the linkage between quantitative modeling and qualitative scenario development (cf. section 5). Figure 18 shows the structure of the final consumption module, including import and export connection to the FREM database.

[58] FREM is described in detail in [15]. In this dissertation FREM is used both as a database to store primary data, preliminary and final results as well as a calculation tool for disaggregating NUTS-0 final consumption data to hourly load curves at NUTS-3 level.

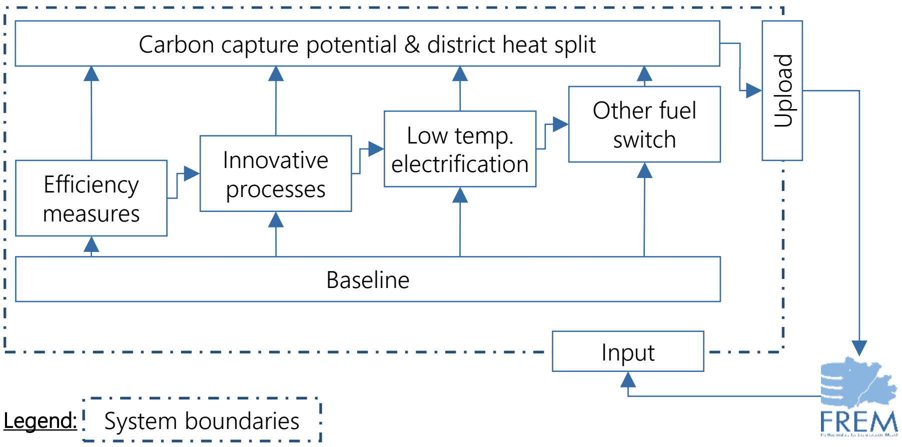

Figure 18: Final consumption module SmInd EU including link to FREM database

In the baseline calculation, the final energy and feedstock consumption as well as process emissions are calculated for each region and time interval. The model time horizon is 2017 to 2050, with annual time intervals. FC is calculated for 13 industry branches, 27 industrial process, 12 applications, 14 energy and 4 feedstock carriers. The baseline calculation is followed by the implementation of greenhouse gas abatement measures, which are structured into the four implementation clusters; efficiency measures, innovative processes, low-temperature electrification and other fuel switch measures. Each measure cluster is constructed so that it can be applied individually on top of the baseline calculation. For this dissertation, abatement measures are parametrized so that measure interdependencies are respected, if the order implied by the stepwise structure in Figure 18 is followed. Preceding the upload of the model results into the FREM database, the carbon capture potential and district heat split is calculated. In section 4.1.2 the parametrization and main algorithms for SmInd EU are described. To facilitate the understanding of the mathematical expressions and thereby the functionality of the model, the concepts of calculation layers and aggregation levels are explained beforehand (cf. section 4.1.1).

4.1.1 SmInd EU Calculation Layers and Aggregation Levels

SmInd EU has three main layers of operation: the industry branch, process, and CO_2 abatement measure layer. The data aggregation levels vary between and can vary within a layer depending on the respective calculation. These differences and the necessity to switch aggregation levels are mainly driven by the granularity of the available input data. Examples A through D in Figure 19 detail these concepts.

Examples A and B illustrate different aggregation levels of final consumption in the industry branch layer. The indices in example A show that final consumption is given at country, industry branch, year and energy carrier type level (e.g., fuel). The layer and aggregation level in this example are required to calculate the effect of economic development on final consumption. However, more detailed data at industry branch level is required to model the effect of abatement measures on industrial emissions. To switch between the aggregation levels in example A and B an allocation key termed the *energy carrier type application share* is used. This allocation key provides information about the shares of energy carriers and applications within a country, industry branch and energy carrier type. In turn, moving from more to less detailed aggregation levels are performed by calculating the sum over various parameters.

Example C shows the term used to express final consumption at process level with respect to the country, industry branch, process, year, and energy carrier. Example D depicts the change in final consumption due to a process measure at country, industry branch, process, measure, year, and energy carrier type level. To write the change in final consumption into the industry branch and process layer, compatibility between the aggregation level in each layer is required. For compatibility with the process layer aggregation level in example C, the change in final consumption at measure level requires disaggregation from energy carrier type to energy carrier level and aggregation over all implemented measures. The result is the change in final consumption at country, industry branch, process, and energy carrier level. The latter can then simply be added to the final consumption in example C. To achieve coherency between the aggregation levels on the measure and industry branch layer (example B) a similar operation is performed, however a different allocation key for disaggregation to application and energy carrier level is used.

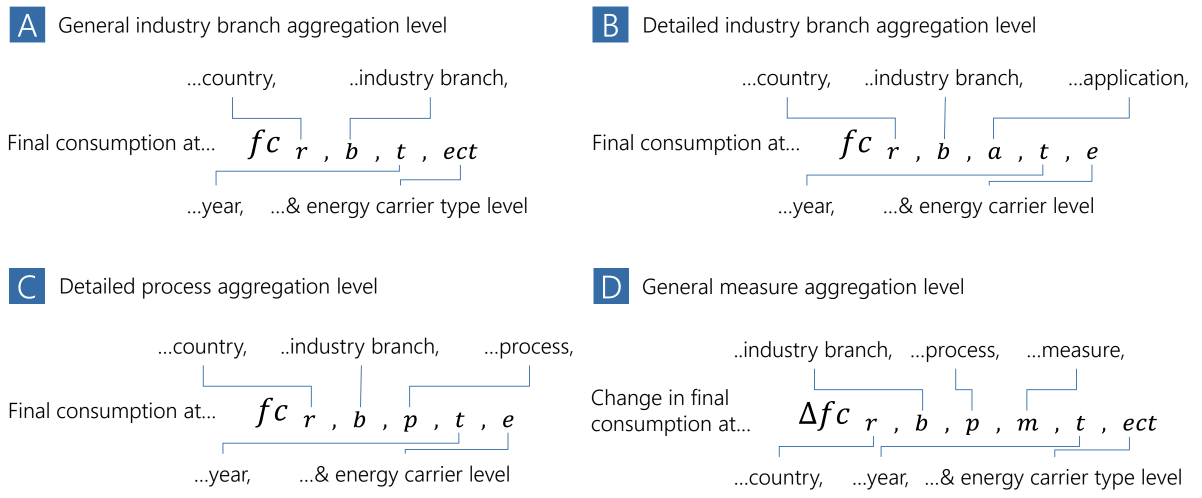

Figure 19: Exemplary aggregation levels for different calculation layers in SmInd EU

Depending on the measure cluster, the changes in final consumption and process emissions are linked to varying model layers at different aggregation levels. Independent of the example, consistency between layers is established through aggregation and disaggregation.

4.1.2 Definition and Implementation of Measure Clusters

In the following sections, the implementation of abatement measures and the effect of each cluster on industry branch and process FC and process emissions are detailed.

Baseline Final Consumption Development

The baseline calculation considers the effect of economic growth and long-term trends in energy intensity development on industrial final consumption until 2050. Since the industry sector is only partially modeled via bottom-up processes, baseline FC and process emission development requires different activity figures for the industry branch and process level.

On an industry branch level, both gross value added and the industrial production index are suitable activity indicators [99]. However, to the best of the author's knowledge, a European long-term industrial activity scenario only exists expressed in terms of GVA. Hence, the GVA scenario in [100] is used as the activity indicator on industry branch level. For the modeled industrial processes, final consumption and process emissions are directly linked to production tonnage development (cf. section 3.2) [17]. The latter is an exogenous model parameter and based on the reference scenario in [52]. Consistency between both activity figures is given for SmInd EU, as production development in [52] builds on the GVA development in [100].[59]

Given the consistency between production tonnage and GVA development, the change in baseline final consumption and process emissions on process level can be calculated separately from industry branch level development. As stated in section 3.2 expressions (3-1), (3-2) and the right side of expression (3-3) are

[59] Production tonnage development can develop contrary to the GVA. For example: the 2050 growth scenario for the iron & steel branch is positive, while overall steel production remains at today's level. GVA increases can result from growth in processes which are not modeled bottom-up and/or because it is expected that the value of the produced goods increases over time.

used to derive the annual final consumption and process emissions at process level. Feedstock consumption and process emissions are modeled at process level. To derive the respective values by industry branch, the sum of all feedstock consumption and process emissions across processes within an industry branch is derived. Process emissions not covered by bottom-up processes are assigned to proxy-process to enable a uniform calculation. The development of process emissions in proxy-processes is assumed to correlate with the average European GVA development in the respective industry branch.

The baseline development at industry branch level solely affects fuel and electricity FEC. While production tonnage development is directly linked to the FEC development and process emissions of a specific process, GVA and industrial FEC development are not perfectly correlated [101, 102]. Especially in developed countries, the energy intensity (MWh/€) of industrial goods has decreased over the past decades. This results from a decoupling of FEC and GVA development. Depending on the industrial good, one or more of the following factors triggered this development [101, 102]:

- The real value of the good has increased, while the energy demand for production stayed constant
- The structure of the industry sector has shifted towards products with lower energy intensities and/or the import of intermediate goods has increased, leading to a higher intermediate consumption intensity
- Energy efficiency progress leads to lower FEC per unit of output

Consequently, to use GVA as an activity figure to model FC at industry branch level, a scenario for the change in energy intensity development is determined. Subsequently, the annual change in baseline FC at industry branch level is calculated according to expression (4-1).[60]

$$\Delta fc_{r,b,t,ect} = \Delta ei_{r,b,t,ect} \cdot \Delta gva_{r,b,t} \; with \; ect \; \in fuel, electricity \quad (4\text{-}1)$$

r: region b: industry branch t: year gva: $gross\ value\ added$
fc: final consumption ei: energy intensity ect: energy carrier type

The energy intensity development is calculated for each country, industry branch and energy carrier type. It is based on an extrapolation of the historical energy intensity development for each country, industry branch and energy carrier type. Before the extrapolation is performed, historical FEC values are adjusted for technical efficiency gains and efficiency losses.[61] Hence, the energy intensity excluding efficiency gains and losses is used as a basis for extrapolation. This step is performed to avoid double balancing of efficiency improvements resulting from efficiency measure implementation until 2050.

This is done by disaggregating the annual changes in FEC between 2009 and 2017 into a quantity and a unit consumption component based on [103–106]. Afterwards, FEC values excluding the unit consumption effect are calculated. The resulting FEC can be interpreted as *the FEC that would have occurred if, ceteris paribus, specific (fuel and electricity) consumption remained at the level of the base year.* This so-called *FC excluding efficiency gains (and losses)* is then used to calculate the historical energy intensity (2009 – 2017) without efficiency gains (or losses). Figure 20 compares Germany's industrial fuel and electrical intensity with and without accounting for efficiency gains.

[60] Baseline feedstock development is calculated at process level and therefore linked to production tonnage development.
[61] Efficiency losses result from imperfect utilization of industrial production equipment [103].

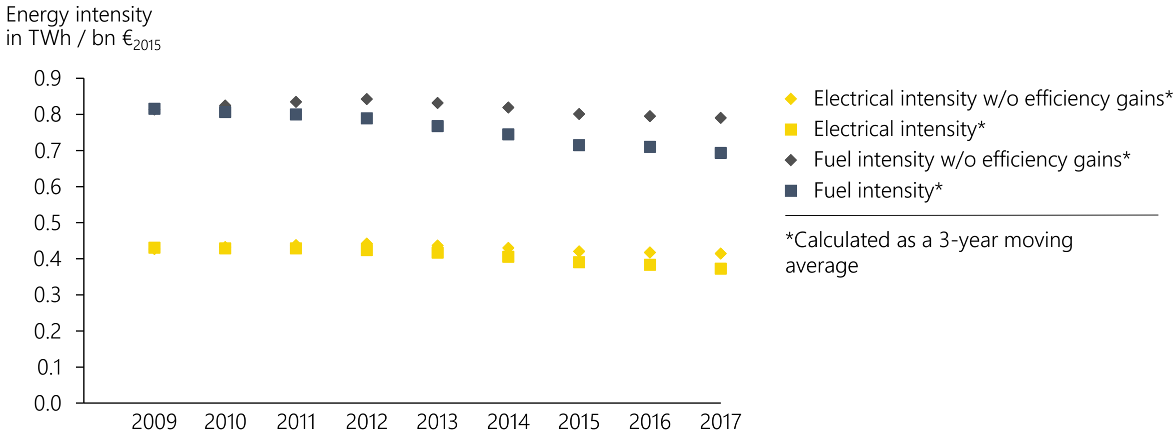

Figure 20: Energy intensity development in the German industry sector incl. and excl. efficiency gains[62]

The diagram shows that excluding efficiency gains from FEC development results in higher energy intensity values compared to actual energy intensity values in the respective year. It also shows that efficiency gains contributed to energy intensity reduction in the past. Nevertheless, energy intensity decreases despite controlling for efficiency gains, showing that value and/or structural effects also lead to energy intensity reductions.

To derive the annual change in energy intensity excluding efficiency gains until 2050, the trend between 2009 and 2017 is extrapolated. Hereby, a logarithmic trend extrapolation is selected. It reflects a saturation effect with respect to energy intensity changes because of structural and/or value effects. This means that it is assumed that shifts towards higher value products and or product value increases behave asymptotically. It can also be interpreted as a dampening effect, which reduces the influence of GVA on the FEC development [101]. Ultimately, the compounded annual growth rate for the change in energy intensity between 2017 and 2050 is calculated for use in expression (4-1).

The resulting absolute FEC at industry branch level is derived using the expressions (4-2) and (4-3). Via the allocation key in expression (4-3) changes in fuel and electricity consumption are disaggregated to energy carrier and application level. In the baseline calculation, the $ectas$ values within a country and industry branch are assumed constant at 2017 values since there are no structural changes in industrial processes.

$$fc_{r,b,a,t,e} = fc_{r,b,a,t-1,e} + \Delta fc_{r,b,a,t,e} = fc_{r,b,a,t-1,e} + \Delta fc_{r,b,t,ect} \cdot ectas_{r,b,a,t,e} \tag{4-2}$$

$$ectas_{r,b,a,t,e} = \frac{fc_{r,b,a,2017,e}}{fc_{r,b,2017,ect}} \quad with\ ect \in fuel, electricity \tag{4-3}$$

fc: final consumption $ectas$: energy carrier type r: region b:industry branch
a: application t: year e:energy carrier ect: energy carrier type

In conclusion, the baseline calculation considers the effect of economic growth and long-term trends in energy intensity development on industrial FEC until 2050. The resulting FEC can be interpreted as the final energy consumption that would occur because of GVA growth, if production efficiency would remain at

[62] All data taken from [23, 31]. Real GVA is calculated as the difference between real production value (rPV) and real intermediate consumption (rIC) for all countries and industry branches [99]. rPV and rIC are realized using the country and industry branch specific industrial producer price index [30]. 2009 is used as a base year for the calculation for several reasons: i) it marks the end of the global financial crisis in several countries, ii) [102] show that the role of energy efficiency as an influencing factor for FEC development changed lastingly after the financial crisis, compared to before, iii) all relevant data is available from 2008 onwards, with 2009 being the earliest year with high availability across countries.

the level of 2009, and structural changes in the industry sectors of each country would continue with a gradually decreasing intensity.

Measure Cluster 1: Energy Efficiency

In this section, the method for determining the change in final energy consumption due to efficiency measure implementation on process and industry branch level is explained. The quantification of efficiency measure abatement potential is described in section 3.3.3.

Efficiency measures are applied on top of baseline FEC. These measures do not affect feedstock consumption and process emissions. Hence, only the energy carrier types fuel and electricity are addressed. The change in fuel and electricity FC due to measure implementation is derived by expression (4-4) [17].

$$\Delta fc_{r,b,p,a,m,t,ect} = pote_{r,b,p,a,m,t,ect} \cdot er_{m,t} \tag{4-4}$$
$$with\ t = \frac{t - t_{m,start}}{l_m}\ and\ 0 \leq t \leq 1\ and\ ect \in fuel, electricity$$

fc:final consumption	$pote$: technical measure potential	er: exchange rate	m: abatement measure
ect: energy carrier type	r: region	t: year	p: industrial process
l: lifetime of technology	y: year of implementation	b: industry branch	a: application

The starting year of measure implementation can be selected for each of the measures individually [88]. Total measure potential is defined with respect to the production volume in 2017. Measure application ends when the total measure potential is implemented (i.e., $er_{m,l,y} = 1$) or 2050 is reached.[63]

The effect on energy consumption at industry branch and process level are calculated differently, depending on whether a process, CST, or proxy-efficiency measure is implemented. This results from differing calculations with respect to the *energy carrier type application share* ($ectas$). The latter are shares used to disaggregate changes in fuel and feedstock consumption to energy carrier and application level. In the baseline, the $ectas$ values within a country and industry branch remain constant. This is not the case if abatement measures are implemented. In each calculation step, only the final consumption of applications, which are directly addressed by efficiency measures, are affected (cf. expression (4-3)).

$$ectas_{r,b,a,m,t,e} = \frac{fc_{r,a,m,t,e}}{fc_{r,a,m,t,ect}}\ or\ ectas_{r,b,a,m,t,e} = \frac{fc_{r,b,a,m,t,e}}{fc_{r,b,a,m,t,ect}}\ with\ ect\ \in fuel, electricity \tag{4-5}$$

$$fc_{r,b,p,t,e} = fc_{r,b,p,t-1,e} + \Delta fc_{r,b,p,t,e} = fc_{r,b,p,t-1,e} + \Delta fc_{r,b,p,m,t,ect} \cdot ecs_{r,b,p,t,ect,e} \tag{4-6}$$

$$sc_{r,b,p,t,ect} = \frac{fc_{r,b,p,t,ect}}{pt_{r,b,p,t}}\ with\ fc_{r,b,p,t,ect} = \sum_e fc_{r,b,p,t,e}\ for\ all\ e \in ect \tag{4-7}$$

$ectas$: e type a share	fc: final consumption	ecs: energy carrier shares	sc: specific consumption
pt: production tonnage	r: region	b: industry branch	a: application
m: abatement measure	t: year	ect: energy carrier type	e: energy carrier

For CST measures the $ectas$ is calculated based on the total industrial FEC of the addressed application in a country (cf. left part expression (4-5)). For process and proxy measures, the industry branch specific FEC is used (cf. right part expression (4-5)). The resulting change in FEC at industry branch level is subsequently determined using a variation of expression (4-2).

On the process level, final consumption and the resulting new specific consumption values are calculated using expressions (4-6) and (4-7) [33]. Compared to the industry branch level, the $ectas$ is replaced with the energy carrier shares. The latter are country, industry branch, process, time, and energy carrier specific.

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[63] In case of production tonnage growth, the additional production tonnage receives the efficiency standard of the respective year.

Changes to process emissions and feedstock consumption do not occur due to efficiency measures. Using the above-mentioned expressions, the change in energy consumption on industry branch and process level as a result of efficiency measure implementation is calculated. Depending on the scenario, the calculation of further measure clusters can be performed (cf. Figure 18).

Measure Cluster 2: Innovative Process Substitution

The substitution of process routes is a process specific measure which is modeled as a shift of production tonnages from one process to another. This measure cluster affects FEC, feedstock consumption and process emissions. Expression (4-8) shows how the change in production tonnages is determined for each process substitution measure.

$$\Delta pt_{r,b,p,m,t} = pt_{r,b,p,t} \cdot af_{m,2017} \cdot er_{m,l,y} \tag{4-8}$$

$$\Delta fc_{\mathrm{r,b,p,t,e}} = \sum_{m} \Delta pt_{r,b,p,m,t} \cdot sc_{r,b,p,t,ect} \cdot ecs_{r,b,p,t,ect,e} \tag{4-9}$$

$$\Delta pem_{r,b,p,t} = \sum_{m} \Delta pt_{r,b,p,m,t} \cdot emf_p \tag{4-10}$$

$$with\ ect\ \in fuel, electricity, feedstock$$

pt: production tonnage	af: application factor	er: exchange rate	fc: final consumption
sc: specific consumption	ecs: energy carrier shares	pem: $process\ emissions$	emf: emission factor
r: region	b: industry branch	p: process	t: year
$e(ct)$: energy carrier (type)	m: abatement measure	l: lifetime of technology	y: implementation year

In analogy to the energy efficiency measures, an application factor and maximum annual exchange rate are defined. The latter is defined with respect to the technical lifetime of the process that is being replaced. For primary steel, HVC and cement, the time interval until the next fundamental refurbishment is assumed, as technology lifetimes exceed 50 years.

The change in final consumption and process emissions at process level is calculated based on the change in production tonnages as well as the specific process consumption and the energy carrier shares for each process in the respective year (cf. expression (4-9) and (4-10)). Subsequently it is added/subtracted from the respective process consumption or emissions.

To transfer the change in final consumption and process emissions to industry branch level the difference in energy consumption at process level is further disaggregated to the application level. This is required because the top-down balance operates at energy carrier and application level. To do so, the already energy carrier specific change in process final consumption from expression (4-9) is distributed to the relevant process applications (cf. expression (4-11)). This is done via an allocation key which provides the application split for each energy carrier in the respective industry branch (cf. expression (4-12)). Hereby the underlying assumption is that the application split for each energy carrier at industry branch level reflects that of the modeled process.[64] For feedstock and process emissions this operation is performed for technical reasons, the allocation to applications is however not meaningful.

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[64] An alternative to this method would be using the static shares of process heating and cooling demand by application provided in [22]. The selected method however reduces the chance of receiving negative values in the top-down balance as a result of process substitution measures. Negative values can occur if the assumed and actual energy carrier shares at process level differ significantly for a certain country. The latter cannot be completely avoided due to a lack of energy carrier share data for each process in the EU27+3. Using static process-specific application shares can consequently lead to problems if the absolute FEC for a certain energy carrier in the top-down balance is very low in an application to which a high share of process FEC is allocated. On the other hand, using dynamic application shares to transfer changes in FEC at process- to industry branch-level can lead to inaccuracies in the resulting top-down balance if the application split at industry branch level deviates significantly from that of the modeled process.

$$\Delta fc_{r,b,a,t,e} = \Delta fc_{\mathrm{r,b,p,t,e}} \cdot aps_{r,b,a,t,e} \tag{4-11}$$

$$aps_{r,b,a,t,e} = \frac{fc_{r,b,a,t,e}}{\sum_a fc_{\mathrm{r,b,a,t,e}}} \mid a \in rel.process\ applications \tag{4-12}$$

fc: final consumption aps: application share r: region b: industry branch
a: application p: process t: year e: energy carrier

To derive the change in final consumption and process emissions at industry branch level the result of expression (4-11) is added/subtracted from the respective industry branch final consumption or emissions.

Measure Cluster 3: Direct Electrification

The direct electrification of low- and medium-temperature of industrial process heat is modeled as a cross-sectional measure, which affects the FEC at industry branch level. Unlike the CST efficiency measures, which are also modeled as CSM, the potential of direct electrification measures is calculated endogenously. The calculation builds on the FEC after the implementation of cluster 1 and 2 measures. This order is important because implemented efficiency and process route substitution measures change the specific heat demand by company, thereby affecting specific energy savings (both negative and positive) resulting from direct electrification. Fuel savings and additional electrical energy consumption are modeled using utilization factors of an average conventional industrial gas condensing boiler and an alternative electrical technology. The measures are parametrized so that the calculation of the total measure potential can be derived using expression (3-4) and the change in final energy consumption using expression (4-4). Hence, positive specific fuel and negative electricity savings are calculated based on expression (4-13). To do so, the heat demand for both temperature levels is calculated based on the fossil FEC within the respective country and application (cf. expression (4-14)).

$$ses_{r,a,m,t,ect} = \frac{hd_{r,a,m,t,ect}}{\eta_{m,sub}} \tag{4-13}$$

$$hd_{r,a,m,t,ect} = \frac{\sum_{a,ect} fc_{r,a,t,ect} \cdot \eta_{m,ref}}{c_{r,m,t}}$$

$$with\ ect\ \in fuel, electricity \mid a \in PH \leq 100°C, 100°C > PH \leq 500°C \tag{4-14}$$

ses: specific energy savings hd: heat demand η: utilization factor fc: final consumption
c: no. of companies r: region a: application m: abatement measure
t: year ect: energy carrier type ref: reference $measure$ sub: substitute measure

The resulting change in FEC at industry branch level is subsequently determined using a variation of expression (4-2).

Measure Cluster 4: Other Fuel Switch Measures

In measure cluster 4, fossil energy carriers are replaced using emission-free alternatives via CSM fuel substitution measures. These measures are grounded in technological reasoning, but their parametrization is not technology specific. They address shares of the FEC, for which the underlying technological structure is unknown. Furthermore, the remaining solid fuels in industrial processes are substituted through biomass-based alternatives. Hence, a specific energy carrier in a certain application is targeted at the industrial process and branch level. Expression (4-15) calculates the potential of cluster 4 measures.

$$pote_{r,a,m,t,e} = \sum_{a,e} fc_{r,a,m,t,e} \tag{4-15}$$

$pote$: measure potential fc: final consumption r: region a: application
m: abatement measure t: year e: energy carrier

The change in FEC at industry branch and process level due to cluster 4 measure implementation are derived using expressions (4-4). Subsequently the change in energy consumption for each energy carrier in the respective application level is added/subtracted from the respective industry and process consumption.

Carbon Capture Potential and District Heat Split

This section describes how carbon capture measures and industrial district heat are modeled in SmInd EU. Both aspects are linked to the functioning of SmInd EU as a part of the model landscape described in section 2.

In the context of the model landscape in which SmInd EU is embedded, the decision to implement carbon capture measures is shifted to the supply-side cost-optimization model ISAaR. This is done by communicating a country and process-specific CC abatement potential to ISAaR. The share of abatable emissions is defined exogenously. The absolute potential is a result of the exogenous share and the actual process emissions which occur in the respective year and which are calculated in SmInd EU. Since the emission factors for several energy carriers are a result of the energy system cost-optimization in ISAaR, only process emissions are communicated as an abatement potential. In the emission abatement evaluation this inaccuracy is corrected via an ex-post calculation in which the share of abated emissions using CC measures is applied to the entire exhaust gas stream. This way, also the effect of BECCS measures is evaluated.

Depending on a variety of aspects it is predominantly the ISAaR greenhouse gas emission reduction restriction which affects the degree to which CC measures are deployed by ISAaR [6]. By shifting the decision to reduce emissions via CC to ISAaR, the optimization model can decide if alternative supply-side measures such as the import of synthetic fuels or further RES expansion are more cost-efficient compared to CC measures in the industry. This ensures that unpopular and costly CC measures are only deployed as a last resort.

The final step in SmInd EU which is performed before results are uploaded to the database FREM is disaggregating the energy carrier district heat to the energy carriers used for its procurement. Thereby, district heat is distributed to these energy carriers based on the energy carrier share for primary energy consumption for district heat production in each EU27+3 country in 2017 [24]. This step is performed due to a limitation of the supply-side model ISAaR, in which the cost-optimal procurement of district heat is determined.[65] Due to computational restrictions the district heat optimization is limited to public district heat networks in the European calculation. The cost-optimal procurement of industrial district heat is currently not within the scope of the model. Due to this restriction, district heat is not treated as a separate energy carrier during the evaluation performed in section 7. The underlying implicit assumption is that the industrial district heat supply structure remains constant over time. In deep emission reduction scenarios this leads to additional demand for emission-free gaseous and liquid synthetic fuels as well as solid biogenic fuels. Hereby the potential benefit of power-to-heat in industrial district heat networks for the integration of vRES is neglected in the overall results. Since the topic is not addressed within the main results, an excursus for Germany in 2030 is provided in section 7.3.

Preliminary Summary

In the previous sections, the basic parameters and algorithms for deriving the industrial annual final consumption and process emissions for the EU27+3 between 2017 and 2050 are described. Results are available at several aggregation levels for industry branches, the modeled processes as well as industrial CO_2 abatement measures. As explained in section 2, SmInd EU results are one of several input data sets for

[65] The district heat split is programmed as an optional module, which is only relevant if SmInd EU is used in the context of the entire model landscape. In case of isolated simulation runs, district heat can be treated as a separate energy carrier.

the energy system model ISAaR. To provide the basis for a temporally and spatially resolved energy system analysis, the output of the final consumption module is disaggregated further in both dimensions.

4.2 Regionalization Module

The spatial resolution of the annual final consumption and process emissions calculated in section 3.1.1 is increased from NUTS-0 to NUTS 3 level using the methodology described in [12, 18, 107], as well as the master's thesis [108], which was supervised by the author. Basis for the regionalization are geolocations and emissions of industry sites as well as employee and population data. While emissions and FC are directly linked, the goal of the regionalization is to distribute FC to NUTS-3 regions, so that the regionalized data can then be used as input for ISAaR. Regional emissions are subsequently calculated based on the respective FEC and emission factors, which in parts result from ISAaR simulations.[66] Figure 21 shows how the results of the final consumption module are processed to NUTS-3 level.

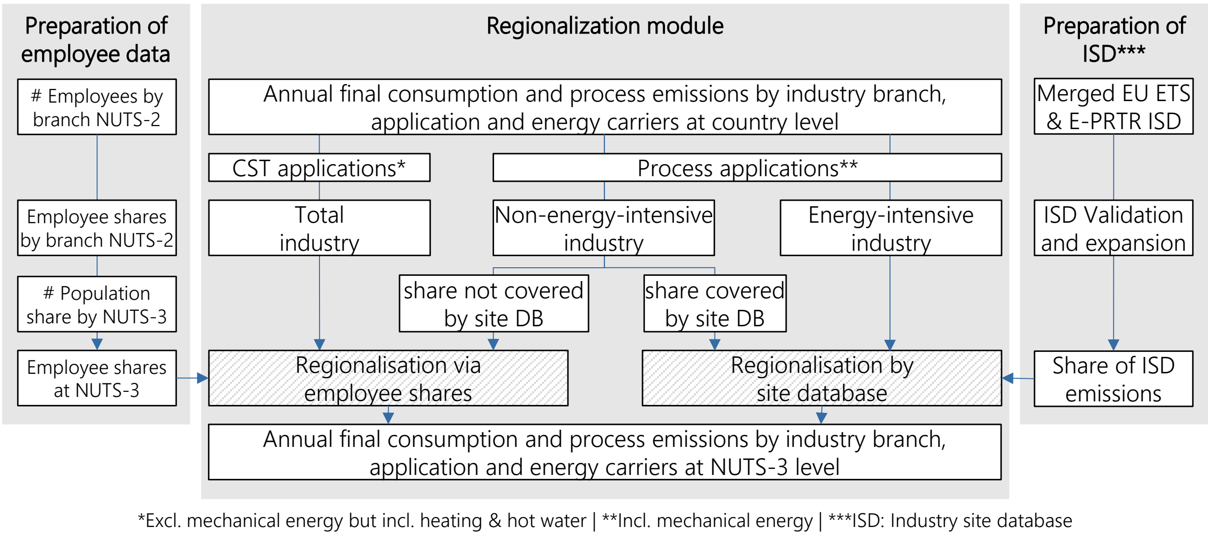

Figure 21: Components and structure of the SmInd EU regionalization module

The starting point for the regionalization module are the SmInd EU final consumption and process emission results at country, industry branch, application, and energy carrier level. In addition, Figure 21 shows that the regionalization module receives two sets of allocation keys as data input:

- the share of employees for each country by industry branch and NUTS-3 region
- the share of emissions for each country by industry branch and NUTS-3 region for the verified emissions in the industry site database (ISD)

Different allocation keys are used to regionalize the FC depending on the industrial application. For the applications process heat, process cooling and mechanical energy in the energy intensive industry, regionalization is performed via an allocation key calculated based on data in the ISD. The same method is used for a part of the final consumption and process emissions in process applications of the non-energy-intensive industry. This part equates to the share of emissions covered by industry sites classified as non-energy intensive in the ISD, compared to the total emissions in the respective industry branch of a country. The remaining process FC and emissions as well as the FEC in CST applications are disaggregated to NUTS-3 level via employee shares. Expressions (4-16) and (4-17) show how the required

[66] The only exception are process emissions, which for the purpose of regionalization are treated like FC for two reasons: 1) Process emission factors are process and not energy system dependent and therefore a direct result of SmInd EU 2) Process emissions categorized as potentially abatable through CC measures are input for ISAaR calculations.

allocation keys are calculated. Expression (4-18) shows how allocation keys are used to disaggregate final consumption.[67]

$$s_{r,N3,b,t,emp} = \frac{emp_{r,N3,b,t}}{\sum_{N3} emp_{r,N3,b,t}} \; with \; a \; \in CST \; \& \; HW \; excl.mech.energy \tag{4-16}$$

$$s_{r,N3,b,t,em} =\cdot \frac{em_{r,N3,b,IS,t}}{\sum_{N3,IS} em_{r,b,N3,IS,t}} \; with \; a \; \in CST \; \& \; HW \; excl.mech.energ \tag{4-17}$$

$$fc_{r,N3,b,a,t,e} = fc_{r,b,a,t,e} \cdot s_{r,N3,b,t} \; with \; s_{r,N3,b,t} \in s_{r,N3,b,t,em}, s_{r,N3,b,t,emp} \tag{4-18}$$

s: allocation key/share	emp: employees	em: emissions	fc: final consumption
r: region	$N3$: Nuts-3 region	b: industry branch	a: application
IS: industry sites	t: year	e: energy carrier	

Two different allocation keys are implemented due to the structural differences between administrative buildings and production sites, which are often at different locations. Energy and emissions from process applications are mainly consumed at production sites with low employee numbers. FEC in CST applications such as lighting or ICT on the other hand mainly occur in administrative buildings characterized by a high number of employees. Regionalization of industrial FC and emissions via one share alone therefore bears the risk of misallocation. This is especially the case for energy-intensive industry branches. In extreme cases strongly staffed administrative centers and highly automated energy-intensive production sites are not located in the same NUTS-3 region. This can result in the misallocation of FC and emissions if regionalization of all applications occurs only via employee shares or the ISD.

To derive the employee allocation key, employee data by industry branch available at NUTS-2 level is disaggregated to NUTS-3 regions [109]. This is done via the share of the population in each NUTS-3 with respect to total population in the respective NUTS-2 region [110].

The starting point for calculating the allocation key used to distribute FC and process emission for process applications is the construction of the ISD. The ISD contains emissions and geographical data for energy-intensive industrial production sites in Europe. These industry site-specific emissions are used to determine how final consumption values for process applications are distributed to NUTS-3 regions within a country and for a certain industry branch. While a distribution via site-specific FEC values would be more intuitive, the procedure is based on emissions because -to the best of the author's knowledge- databases linking geolocations and FEC data of industry sites across Europe do not exist.[68] Due to the high correlation between emission and energy intensity of industry branches in Europe (cf. Figure 6 in section 3.1) this procedure is however considered a sufficiently accurate approximation. The main sources for the ISD are the European Emissions Trading System (EU ETS) and European Pollutant Release Transfer Registry (E-PRTR) emission databases [39, 40] as well as additional sources such as industry branch specific site maps, databases and reports. Figure 22 details the step-wise procedure followed to create the ISD.

The EU ETS includes geodata and verified emissions of ~11,000 power plants and manufacturing installations as well as 600 EU domestic aircraft operators [111]. Amongst others, the industry sites for iron and steel, cement clinker, glass, lime, bricks, ceramics, pulp, paper and board, aluminum, petrochemicals and ammonia production are included [111, 112].[69] Industry installations in the EU ETS verified emissions dataset are categorized differently compared to the NACE rev. 2 classification used in the Eurostat energy balance and SmInd EU calculations. Hence, EU ETS site location data is mapped to the NACE Rev. 2 classification using the information in [113]. Subsequently the dataset is filtered for industry sites for which georeferencing to at least NUTS-3 level is possible (e.g., via a combination of postal and country code if

[67] The same logic applies to the regionalization of process emissions.

[68] In principle, the bottom-up development of a European ISD through manual research of production sites, capacities, utilization rates and specific consumption values is possible, but is out of scope of this thesis.

[69] EU ETS verified emissions database entries for 2015 are used as a basis for regionalization.

the exact address is unavailable). Throughout the described data processing steps installations without verified emissions, identifiable NACE rev. 2 category or address are discarded from the dataset. Ultimately ~4,400 EU ETS installations including geodata and CO_2 emissions are used as input for the ISD.

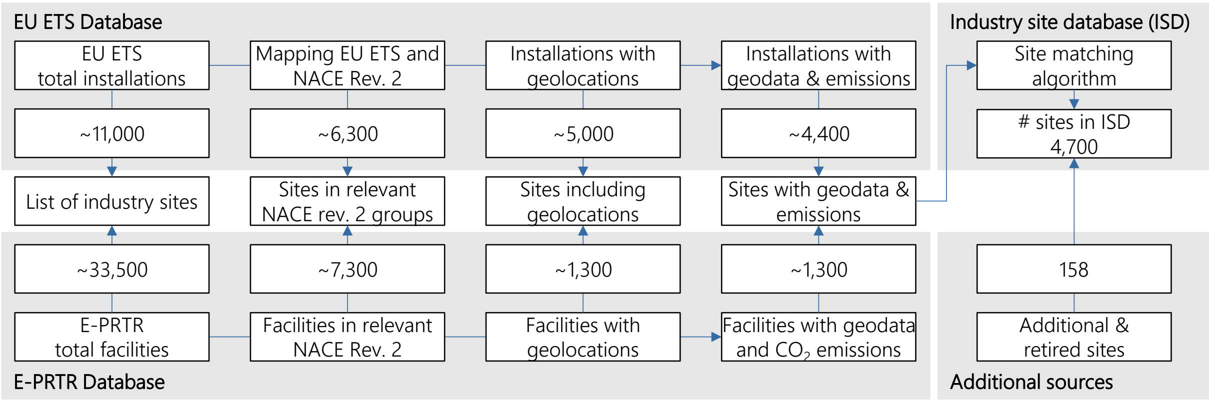

Figure 22: Procedure for developing the industry site database including number of production sites

In addition to the EU ETS industry site specific emission and geodata is collected in the so-called European Pollutant Release Transfer Registry [39].[70] A complete set of the capacity thresholds and other criteria used to define which industrial facilities are obligated to report their emissions can be found in [114]. The E-PRTR database contains information about 91 different pollutants released to air, water, or land in seven pollutant groups and 65 different economic activities. Data filtering steps for the E-PRTR database consequently include the identification of facilities which report CO_2 emissions as well as the facilities in relevant NACE rev. 2 groups including geolocations. Ultimately ~1,300 E-PRTR installations remain as input for the ISD.

Since EU ETS and E-PRTR are two unrelated databases the identified industry sites from both databases are compared using a matching algorithm to avoid double counting. The algorithm compares postal codes, company names and the NACE rev. 2 categories for each entry to first identify and then eliminate duplicate entries. The resulting list of industry sites is validated using energy-intensive industry association data for cement [55], lime [115], chlorine [50], glass [56], steel [116] and steamcrackers [47]. During the validation procedure retired sites are removed from the list and an additional 158 sites are added.

Figure 23 shows the 4,700 industry locations in the ISD. It shows that the geolocations of identified industry-sites with reported CO_2 emissions are more granular than NUTS-3 level. Hence, as shown in expression (4-7), emissions are aggregated to NUTS-3 level by industry branch. Then, these NUTS-3 emissions are set into relation with total emissions covered by the ISD for this industry branch in the country under analysis. The resulting shares are used to distribute FC in process applications and process emissions for the energy-intensive industry as well as a part of the non-energy intensive industry, thereby assuming that the industry locations and employee shares are constant over time. The allocation keys are consequently time and scenario independent.

[70] Version 14 (2019) of the E-PRTR database is used. To achieve consistency with EU ETS dataset 2015 data is used.

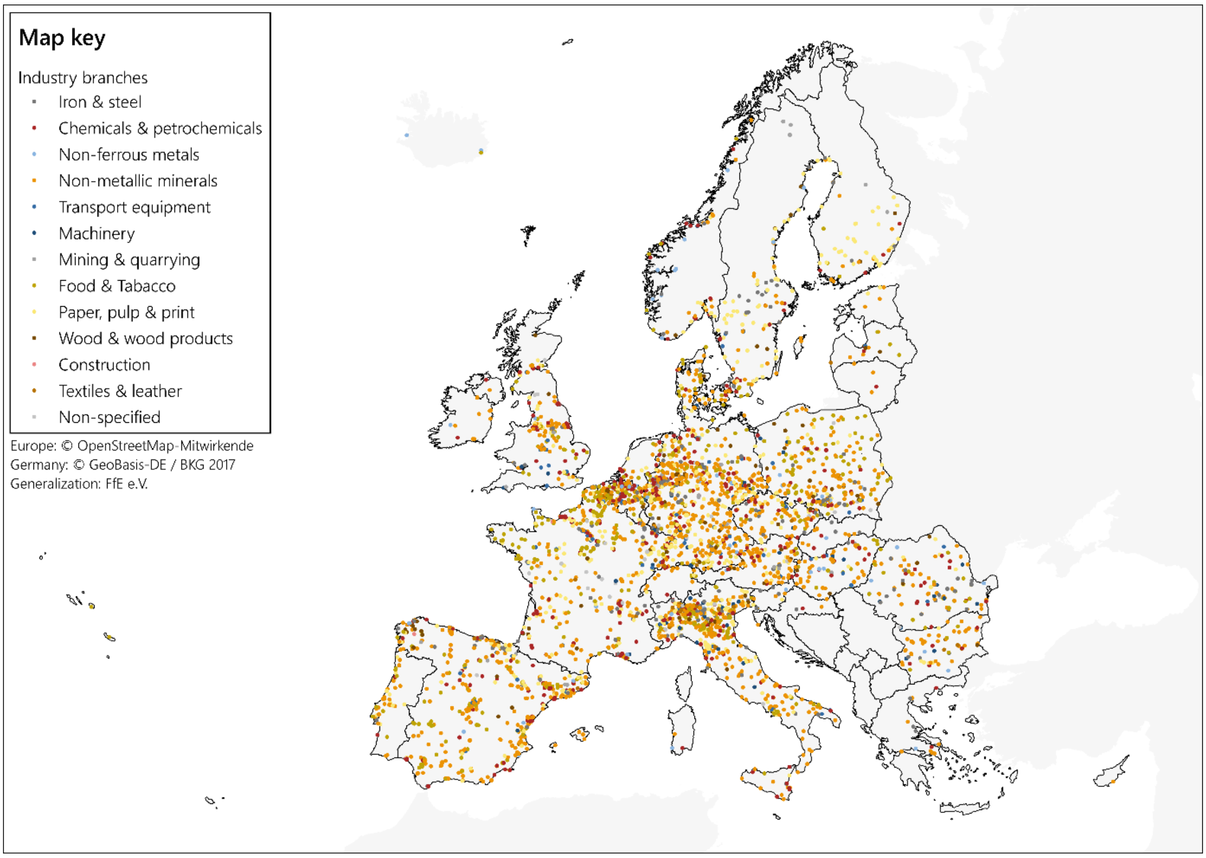

Figure 23: Energy and emission intensive industrial sites in Europe[71]

The described regionalization enables the analysis of final consumption and process emission results at country, industry branch, application, and energy carrier level for every NUTS-3 region in the EU27+3. In the following section, the temporal resolution is increased.

4.3 Load Profile Module

In the SmInd EU load profile module annual final consumption at NUTS-3 level is disaggregated to hourly load data. To do so, energy carrier and application specific synthetic load profiles are derived. This section is mainly based on the publications [12, 117].

The method for determining synthetic load profiles for all industrial applications except for heating and hot water has been developed over a series of dissertations and publications: [6, 118, 119] and most recently [117]. Hereby synthetic load profiles are derived based on real load data collected in energy audits performed by FfE in Austria and Germany. It includes three steps [117]:

1. data preparation
2. regression analysis
3. load profile synthetization

During the data preparation stage, heating and hot water data is separated from process heat data, negative values in real load curves are eliminated and each load curve is allocated to an industry branch. Each real load curve is then normalized in preparation for use in the regression analysis. The latter is executed for each normalized profile, day-type and hour-of-day. Day-types used are Monday, Tuesday to Thursday, Friday, Saturday and Sunday or public holidays. The underlying assumption for the regression

[71] Previously published in [12].

analysis is that process load profiles are independent of weather conditions. Hence, the only external regression parameter used is the monthly country and industry branch specific production index taken from Eurostat [120].[72] Ultimately, the results of the regression analysis for each profile, day-type and hour-of-day are averaged in a stepwise procedure:

1. Averaging occurs for each company and fuel or electricity, in case more than one load curve from the same company but different years exists
2. Regression results for fuels and electricity within an industry branch and across companies are averaged

The described procedure leads to country specific process heat and electricity profiles for all industry branches except for iron & steel, and paper, pulp and print. Due to a lack of real load curve input data, constant profiles are assumed for these industry branches. Since both industry branches are characterized by high full-load hours, assuming a constant load profile is justifiable. Figure 24 shows the hourly load curve for a typical week in the steel dominated region of Taranto, Italy.

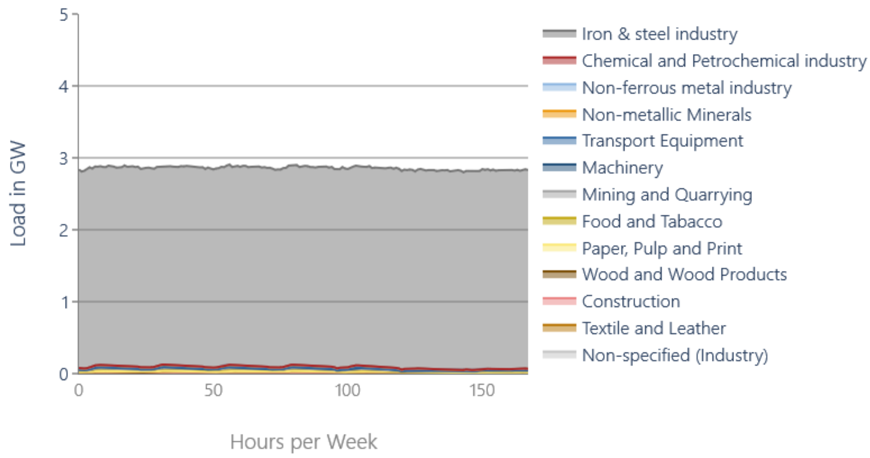

Figure 24: Exemplary weekly load curve by industry branch for total FEC in Taranto, Italy, 2017

For the applications heating and hot water temperature-dependent load profiles from the tertiary sector are used. It is therefore assumed that buildings in the industry sector are similar to those in the tertiary sector [12]. For these space heating profiles degree-day numbers for each NUTS-3 region are considered, in order to reflect the temperature dependency of the application. Hence, regional weather and therefore heating period differences are considered. Figure 25 shows the difference between space heating demand in Oslo, Munich and Naples. To indicate heat demand, the normalized profiles were scaled with the annual total of degree-day numbers. For the analyses in this dissertation the weather year 2012 is used.

[72] In case of data gaps either a country specific branch independent production index or the German branch specific index are used.

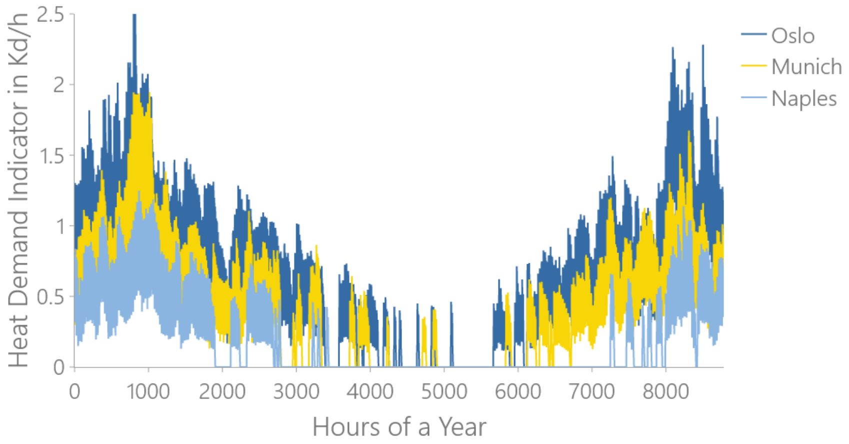

Figure 25: Annual industrial space heating profile for Oslo, Munich and Naples (weather year 2012)[73]

In preparation for a possible scenario-based electrification of industrial space heating, a heat pump profile which is temperature and coefficient of performance (COP) dependent is determined [12]. The profile therefore captures fluctuations in the COP which occur due to variations in the outside temperature.

4.4 Preliminary Summary

Sections 4.1 to 4.3 show how the European industrial energy and feedstock consumption can be modeled in high temporal and spatial resolution. To do so, the industry model SmInd EU was constructed. The model is structured into three modules: final consumption, regionalization, and load profiles. The combination of results from each module enables the analysis of final consumption and consequently emissions for all 1348 NUTS-3 regions in Europe, in hourly resolution. Figure 26 exemplifies the level of detail in which SmInd EU results can be presented.

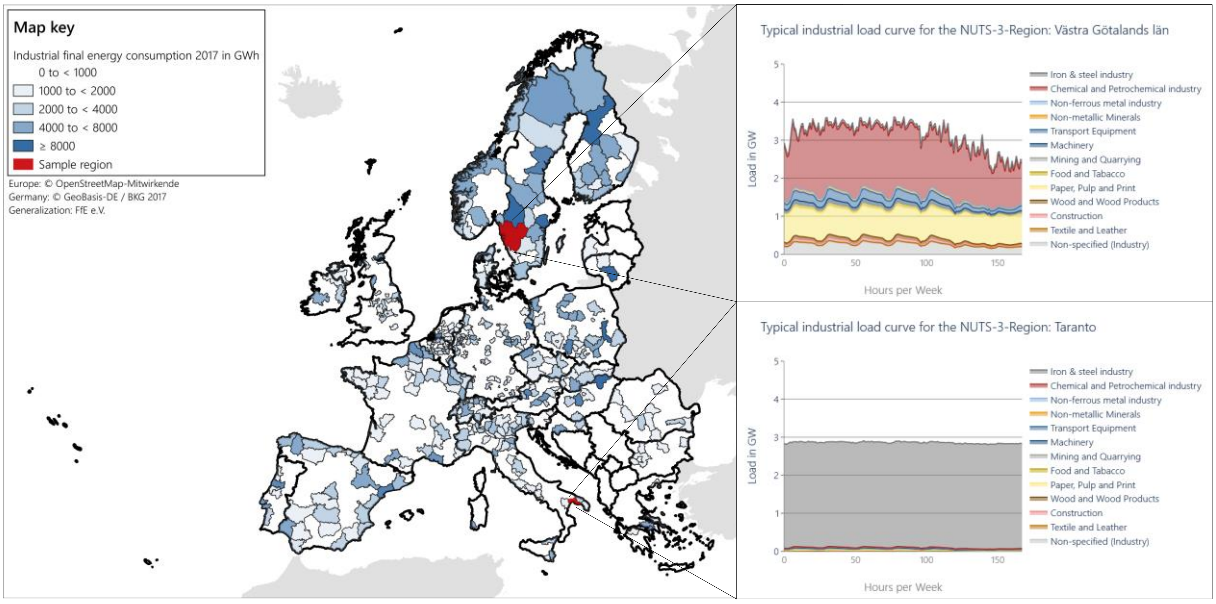

Figure 26: FEC and load curves for typical weeks in the regions Västra Götaland and Taranto

While the presented degree of detail is not necessarily a prerequisite for answering the main research questions in this dissertation it poses a valuable starting point for further research. On the one hand, this

[73] Previously published in [12].

data can be used as input data for European-wide electricity, hydrogen and/or carbon transport infrastructure analysis. The latter poses a highly relevant field of research considering that deep emission reduction scenarios exhibit strong increases in electricity, hydrogen and/or SynFuel demand. Furthermore, existing scenarios, including the analysis performed by the author, do not consider the repercussions of deep emission reduction on existing and potentially required transport infrastructure.

In addition, the presented granularity of industrial data can provide a starting point for the identification of regions in Europe which are especially interesting from an industry and energy system perspective. The latter is briefly exemplified by Västra Götaland and Taranto county, which are highlighted in Figure 26. Both regions are industrial load centers in their respective countries. When analyzing the respective load curves significant structural differences can be identified. The weekly load curve for Västra Götaland is characterized by basic chemicals and petrochemicals as well as the paper, pulp and print industry. Additional literature research shows that the region is home to the largest Swedish chemical cluster, in which both organic and inorganic basic chemicals as well as products of special chemical industry are produced [117]. Another major consumer in the region is the energy-intensive pulp production. Both the paper and chemical industries are characterized by relatively constant consumption patterns over the course of the presented typical week. This results from high full load hours which in turn indicate that a large part of the processes in these industry branches operates continuously. Lower loads during the weekend mainly result from the machinery and transport industry branches, which reduce their production during the weekend. Compared to Västra Götaland, the Italian Taranto is less heterogeneous and mainly characterized by metal production. Taranto is the only Italian primary steel plant and produces ~20 % of Italian steel.

The significant difference in regional industrial consumption patterns shows that a European or national analysis is insufficient to capture the diversity of regional challenges associated with the industrial energy transition. SmInd EU facilitates the spatially and temporally resolved analysis of the industrial FC and emissions in Europe, thereby facilitating the identification of regional differences and the associated challenges.

5 Scenario Process – From Word to Value

In the previous section, the quantitative industry model SmInd EU was formalized. It shows that energy and feedstock consumption development in SmInd EU, and consequently the resulting emissions and associated costs, depend on the quantification of several model-exogenous parameters (e.g., GVA development). Hence, a scenario framework which facilitates the plausible quantification of these parameters, is required. The quantitative values assigned to these parameters are connected to reasoning, by embedding SmInd EU in a socio-political context [121]. For this, a scenario process is developed and implemented, in which qualitative scenario storylines are translated to quantitative input data for SmInd EU. In this dissertation, the disciplines of storytelling and quantitative simulation are consequently combined [122–124]. To do so, the existing cross-impact balance and simulation approach (CIB&S) [124] is augmented by the so-called *From Word to Value* procedure (cf. Section 5.1). The resulting integrated scenario process is then applied to derive two socio-technical European energy system scenarios in section 5.2.

5.1 Scenario Process Definition

In the context of this dissertation a scenario is defined as a plausible path leading towards a version of the future [125].[74] In general, methodologies for deriving scenarios can be characterized as quantitative (i.e. model-based) or qualitative (i.e. storylines) [124]. Due to the multi-disciplinary nature of the (industrial) energy transition, a combined approach is designed and implemented in this thesis. The aim is to derive a socio-technical scenario in which both qualitative and quantitative aspects of the energy transition are accounted for [7]. Through this, the explanatory value of the scenarios is improved since further insights about the reasoning behind the quantitative development can be provided. Furthermore, scenario communication is enhanced, because qualitative reasoning is more accessible for a broader range of stakeholders [7].

According to [7], so-called combined scenario approaches are state-of-the-art in environmental research and have been receiving increased attention in socio-technical energy scenarios over the past years. Figure 27 shows the methodological developments in combined scenario approaches for socio-technical energy and socio-environmental scenarios since 2008.

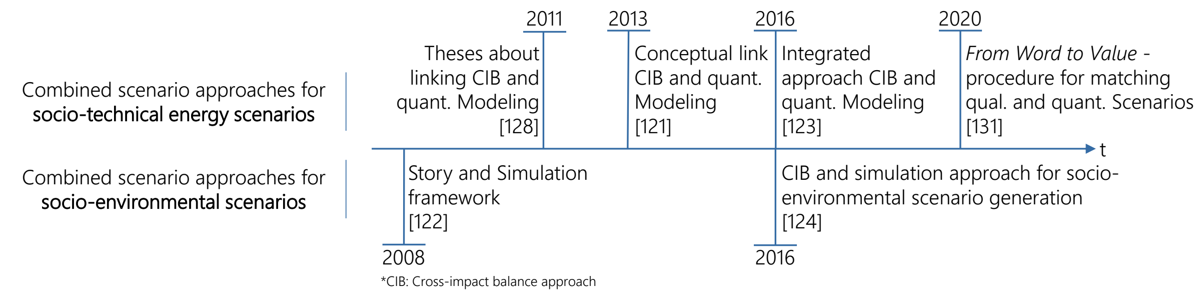

Figure 27: Landmark publications for combined scenario approaches

The *Story and Simulation (SAS)* approach described in [122] marks the starting point of a wave of combined scenario literature published since 2008. SAS can be considered a framework for combining qualitative and quantitative scenarios in a joint process [124]. It is based on deriving scenario storylines using the intuitive logics (IL) approach and translating these storylines to numerical input data sets used in quantitative models. Hereby, storylines created using IL are based on group discussions [7]. The mental models of the

[74] This is to be differentiated from forecasts, projections, or prognoses, which describe expected future pathways.

participants are made explicit by articulating them in discussions and subsequently putting them into writing [126, 127]. Elemental to SAS are the iterations between qualitative and quantitative scenario developers aimed at increasing the degree of integration of the two scenario types [122, 124].

Based on the idea portrayed in SAS, Weimer-Jehle and Kosow began developing combined scenario approaches based on qualitative scenarios constructed using the cross-impact-balance (CIB) method [127]. To date, the prevailing opinion in scenario literature is that CIB is a superior fit for combined scenario construction compared to IL [7]; the major reason being that the CIB method is grounded in mathematics and therefore more systematic. This in turn leads to improved traceability of the qualitative scenario process and increased consistency of the resulting storylines [7, 121, 123, 124, 128]. Hereby, traceability refers to the ability to understand the scenario process as well as the assumptions and their justifications. Consistency refers to the coherency of the resulting qualitative scenario (and not the process) [124, 126].[75] Kosow built on this line of argumentation and published the cross-impact-balance and simulation (CIB&S) approach for socio-environmental scenarios in 2016 [124]. In the same year, the socio-technical energy scenario approach was published [123]. Both methods essentially describe the combination of qualitative scenario storyline development using the CIB approach and translating this scenario to a numerical input data set for quantitative modeling in the respective field. The meta-analysis in [7] shows that since 2016, a variety of socio-technical energy scenarios in line with the CIB&S and socio-technical energy scenario approach have been published. Recent examples for publications including elaborate documentation of the approach, assumptions and results are [129, 130].

Figure 28 shows the steps of the CIB&S approach as described in [124] and how it is expanded using the FWV procedure in this thesis.[76]

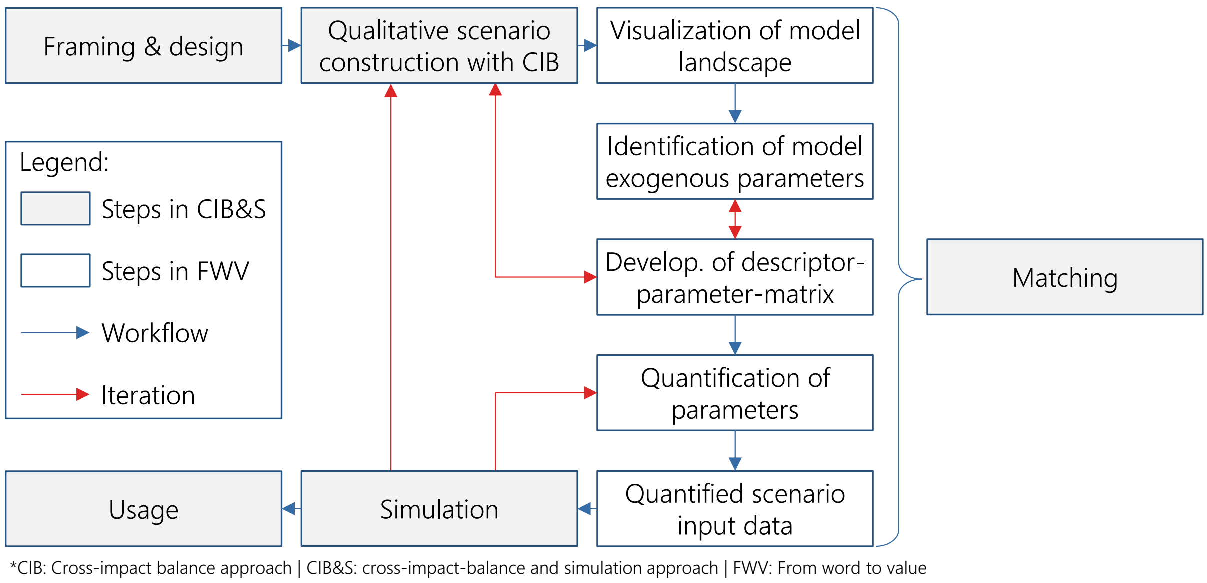

Figure 28: Expansion of CIB&S approach through the F*rom Word to Value* procedure[77]

While [123, 124] detail that the context scenario "… is 'translated' into a specific set of model input parameters by a joint exercise of context scenario constructors and energy model experts" [123, p. 960], and "… qualitative scenario construction is linked with numerical modeling" [124, p. 90] in the matching stage, a practical formalization of this step is not described. The more recent combined scenario literature such as [129, 130] provide details on how the matching between descriptors and parameters was performed,

[75] Traceability and consistency have emerged as the main quality criteria for evaluating scenario processes and scenarios [126].
[76] While the socio-technical approach in [123] declares the individual steps of the combined scenario approach differently, the process is essentially the same as CIB&S.
[77] CIB&S steps are from [124].

but do not abstract a general procedure.[78] Figure 28 therefore shows how the FWV procedure is used to formalize the matching process [131]. Through the FWV procedure, the traceability of the matching procedure is improved, since the matching steps are formalized and a documentation guideline is provided. The FWV procedure is applicable to qualitative scenarios which are derived using the CIB approach, since it proposes the matching of descriptors and parameters in step 3. Intuitive scenario approaches work without descriptors and do not allow for such a structured link. The following sections provide an overview of each step of the combined scenario process in this dissertation, in preparation for its application in the following section 5.2.

5.1.1 Framing, Design and Qualitative Scenario Construction

In the first step of the scenario process shown in Figure 28, the goal and topic, as well as geographical and temporal scopes of the context scenarios are defined. Furthermore, procedural aspects are decided, such as the method for qualitative scenario creation, the models used for scenario quantification, and the design of the iterative procedure between qualitative scenario and quantitative modeling experts [124].

In step two of the scenario process, storylines based on the CIB method described in [127] are derived. At the core of CIB lies an algorithm with which the mathematical consistency of different scenarios is evaluated. In CIB, the scenario world is described through a set of descriptors which each assume different trends/futures. The interdependencies between descriptor trends are assessed based on literature review and/or expert interviews. The strength and direction of interdependencies are often quantified using a seven-point scale ranging from – 3 (strongly restricting) to + 3 (strongly promoting). The resulting quantified interdependencies are summarized in the so-called cross-impact matrix. The algorithm ultimately iterates through this matrix and selects sets of trend combinations which fulfill the self-consistency criterium. These combinations pose the resulting set of consistent scenarios. The latter are subsequently clustered and verbalized to provide the storylines also referred to as qualitative scenarios.

As mentioned above, the two main qualitative scenario techniques used in combined scenario approaches are the CIB and IL method. Compared to IL, the CIB method is relatively young (1987 vs. 2006) and application cases are fewer. Nevertheless, the detailed analysis of the strengths and weaknesses of CIB vs. IL suggests that CIB seems to be the superior method for combined scenario approaches. The following table summarizes its main strengths and weaknesses [7].

Table 12: Strengths and weaknesses of CIB in combined scenario approaches[79]

Strengths	Weaknesses
Guarantee of internal scenario consistency	Time-consuming and therefore expensive
Identification of all consistent scenarios	Method experience and preparation required
Improved traceability of the scenario process	Descriptor numbers are limited
Descriptors as anchor points for model parameters	Consistency at the cost of insights
Reduction of subjectivity	Perceived objectification of subjectiveness

One of the main advantages of CIB compared to IL is that the use of a mathematical algorithm ensures the internal consistency of the resulting scenarios. Once the interdependencies between descriptor trends are quantified, the room for human failure is significantly reduced, since a computer calculates the set of consistent combinations. Furthermore, the algorithm ensures that the list of scenarios meeting the consistency criterium is complete. Due to the high degree of formalization, CIB also allows for improved traceability of the scenario process. Firstly, the selection of consistent scenarios follows a traceable set of

[78] Descriptions in the supplementary material of [130] provide the most detail and some components are conceptually similar to the work described here. This is seen as a confirmation and validation of the FWV procedure developed in this dissertation [131].
[79] Own summary based on [7, 121, 123, 124, 128] and own experiences in the eXtremOS scenario process.

rules. Secondly, the assumptions about interdependencies between descriptor trends are made explicit and accessible in the cross-impact matrix. This is especially relevant for combined scenario processes in which different teams are responsible for the qualitative and quantitative processes. Furthermore, the use of descriptors and trends to describe the scenario world poses a structured anchor point for matching model parameters and qualitative storyline. Ultimately, the above-mentioned points support the reduction of subjectivity in the qualitative scenario process (compared to IL), and hence in the combined scenario approach.

Nevertheless, these advantages come at a cost. Due to its technical nature, CIB is time-consuming with respect to preparation, execution, and documentation of the method. Furthermore, it requires a higher level of expertise to be executed, compared to the discussion-based IL method. While the descriptors structure the qualitative scenario process, their number is limited and therefore not all thinkable facets of a future scenario are captured. Typically, scenarios deemed inconsistent by the CIB algorithm are excluded from further analysis, even though insights about the future might also be gained from them. And while formalization supports the reduction of subjectivity, it can also spark the false perception that scenarios constructed using CIB are "objective versions of the future."

5.1.2 From Word to Value - Matching Storylines and Numerical Models

The following sections explain how storylines can be matched to numerical models using the FWV procedure depicted in Figure 28 [131]. Integrated scenarios face the challenges of both numerical and qualitative scenario construction methods. In this sense the control of consistency and traceability for each individual component needs to be mastered, and simultaneously, the connection between both types must satisfy these standards. This is where FWV supports combined scenario construction.

Visualization of Model-Landscape

A prerequisite for quantifying context scenarios is the identification of model landscape exogenous parameters (mexP). The mexP identification procedure begins with creating an overview of the model landscape including model interdependencies and a full parameter list. Thus, the model landscape is visualized in a flowchart, showing how all model input and output parameters are connected. A positive side-effect is that the visualization of the model landscape sharpens the understanding of the model context and functionalities. This is especially useful when models are developed by different teams.

Identification of Model-Landscape Exogenous Parameters

Based on the visualized model landscape and full parameter list, the latter are classified, aiming at identifying mexP, which can subsequently be connected to context descriptors. For this purpose, three types of model parameters are differentiated:

- **Scenario independent mexP** are parameters which can be considered certain or historical input data (e.g., technology lifetimes or energy savings potentials of individual technologies)
- **Scenario dependent mexP** encompasses all parameters for which assumptions about their future development are required (e.g., production tonnage development)
- **Scenario dependent model endogenous parameters (menPs)** are parameters which result from model calculations within the defined model landscape (e.g., final energy consumption in 2050)

Relevant for the further FWV procedure are mexPs, which are considered exogenous from the perspective of the entire model landscape. For example: electricity consumption in the industry sector in 2050 is an exogenous parameter from the perspective of the energy system model ISAaR. However, from the perspective of the model landscape, industrial electricity consumption is an endogenous parameter as it is a result of the calculations performed using SmInd EU. To ensure the consistent quantification of context scenarios across all models, it is necessary to ensure that mexPs which are input to several models (e.g., GVA development) are assigned only one set of values.

Development of Descriptor-Parameter Matrix

In this step of the FWV procedure, previously identified scenario dependent mexPs are matched with the descriptors defined in the qualitative scenario construction phase (cf. Figure 28). The degree of integration between qualitative and quantitative scenario development impacts to what extent links between model parameters and descriptors can be drawn. Three stages of links are defined[80]:

- A **direct link** exists if the descriptor is also a model parameter or translates to a direct influence on one or more parameters. In rare cases the descriptor trend is numerical, and the parameter value therefore set by it. For example: the link between the scenario descriptor *gross value added* and the homonymous parameter in SmInd EU is direct.
- **Weak links** occur in situations where the descriptor impacts one or more model parameters but is not equatable to them. For example: the descriptor *innovative capacity* directly impacts the earliest point of availability of (industrial) abatement measures which are currently in the research and development stage. For such measures additional public or private funding is required to develop these technologies to a stage where they are applicable on an industrial scale. It therefore indirectly impacts the parameter *measure start* in SmInd EU. If links between a parameter and several interconnected descriptors exist, the links should be drawn as closely as possible to the root-cause descriptor. This entails identifying and understanding descriptor interdependencies, which facilitates a deeper understanding of the sociopolitical interdependencies between descriptors and their effect on model parameters.
- **No direct or weak link** between descriptor and parameter is drawn if the connection either does not exist or can only be drawn if several intermediate explanatory steps are required. In such cases the descriptors provide context to the scenario, but do not impact the quantitative scenario directly. However, these descriptors can impact descriptors with direct or weak links and consequently affect the quantified scenario indirectly [132]. For example: the descriptor *forms of governance* is not parametrized in SmInd EU. Nevertheless, it impacts the *innovative capacity* descriptor which has a weak model link. It therefore affects the quantification indirectly [133].

Parameters and descriptors interdependencies are recorded in the descriptor-parameter-matrix (DPM). By evaluating the rows and columns of the DPM, frequently addressed parameters and descriptors can be identified. If a parameter is addressed by multiple descriptors, the value assigned to the parameter during the quantification procedure needs to be consistent across all descriptors and their assumed trends in each scenario. For descriptors addressed by several parameters, comprehensive descriptions in the formulated storylines are required to support consistent parameter quantification.

In addition, the DPM can also be used to identify unaddressed descriptors and parameters. If descriptors or parameters critical to the analysis at hand are not linked, further iterations are required (cf. red connections in Figure 28). This can lead to the addition or redefinition of a storyline descriptor or quantitative exogenous model parameter, ultimately allowing for additional links in the DPM. If an important descriptor does not connect to any of the mexPs, an additional parameter can be added to one of the models in the scope of the analysis. If a mexP is not addressed by any descriptor, the parameter is not within the context scenario horizon. If this does not suit the framing and design of the analysis, descriptors can be redefined or added.

Considering that model landscapes used for technoeconomic energy system analysis can encompass several hundred parameters, linking all mexPs to descriptors can be impracticable [132]. If this is the case further literature research might be required to expand the storyline to include details about parameters which cannot be linked to descriptors.

[80] This approach is similar to the one described by [130, 132], in which the terms *hard* and *soft coupling* are used.

Quantification of Parameters

In the quantification stage of the FWV process mexP as well as other input data are quantified in preparation for model simulations. Using the DPM as a starting point each mexP with a direct or weak link to a descriptor is quantified. Hereby, the assigned values can differ depending on the trends the descriptors assume (i.e., they are scenario dependent). Furthermore, methods used to quantify parameters depend on whether the descriptor trends are qualitative or quantitative.

- Descriptors with quantitative trends: the parameter is addressed by a descriptor with concrete values as trends. In this case, these values are assumed for the respective parameters
- Descriptors with qualitative trends: to translate qualitative trends to quantitative values ideally distinct value intervals for each trend are determined from literature research, expert estimates and/or meta-analyses. The values which are ultimately assigned to parameters should allow for a clear distinction between descriptor trends

Independent of whether the descriptor trends are qualitative or quantitative, the quantification step cannot be systemized completely. Despite thorough research and experience of the researcher(s) performing the quantification, a certain degree of subjectivity resulting from both the definition and interpretation of descriptor trends is inevitable. This however is not necessarily a disadvantage since further interpretation of the researcher might be required in case the qualitative scenario does not provide sufficient context for traceable quantifications. In such cases the researchers' expertise becomes instrumental to scenario quantification.

In addition to the quantification of the matched scenario dependent mexPs, scenario independent as well as unmatched mexPs are quantified. For parameters with clear technoeconomic boundaries (e.g., efficiencies for incumbent heating technologies) the room for interpretation during quantification is low. Other parameters (e.g., cost data of innovative technologies) can leave more room for interpretation, especially if no direct or weak links to descriptors can be quantified. As suggested by [132] such data should be quantified "(…) according to the 'spirit' of the given scenario" [132, p. 9]. This quantification step concludes the FWV procedure.

5.1.3 Simulation and Usage of Scenarios

The quantified scenario dependent and independent mexPs are the starting point for model simulation runs. Since one of the main purposes of simulations is to generate new insights about the model's endogenous parameters and thereby the scenario, their outcome can be considered unpredictable. Therefore, simulation results can lead to inconsistencies between storylines and the quantitative scenario, especially when descriptors that address model endogenous parameters exist. Assuming that the modeled quantitative parameter connections are consistent, two possible iterations can be purposeful [124]:

- The CIB and/or storyline are revised to incorporate insights of the quantitative analysis in the scenario storyline
- Parameter quantifications are adjusted, requiring additional model simulation runs and consistency checks

The degree to which storyline and quantitative scenario consistency is necessary depends on the scenario usage. As pointed out in [124] scenarios are mainly used to explore alternative futures, support decision-making, gain a deep understanding of a topic and communicate and raise awareness.

5.2 Scenario Construction – Deriving quEU and solidEU

In this section, the scenario process in Figure 28 is used to derive two socio-technical energy scenarios. The scenarios were derived in the research project eXtremOS [16]. The author of this dissertation was part of the eXtremOS project management team and developed the combined scenario process as well as industry sector model SmInd EU. In eXtremOS, the integrated scenario procedure was applied to the entire model landscape as explained in section 2. The developed scenarios are therefore holistic energy system scenarios. Since the focus of this dissertation is the industry sector, the quantitative scenario development is constrained to the parameters of the industry model SmInd EU.

5.2.1 Framing and Design

The framing and design of the scenarios was defined between the eXtremOS project leads at FfE and the Institute for Technology Assessment and Systems Analysis (ITAS) at the Karlsruhe Institute of Technology (KIT). The aim of the scenarios in eXtremOS is to describe extreme sociopolitical, economic and energy-related developments which trigger (extreme) energy system transformation. Hence, the goal of the storylines is to describe the energy system transformation.

The secondary aim, specifically defined for the industry sector, is to explore possible futures for the development and target state of the European industry sector, thereby acquiring an understanding about the core aspects of greenhouse gas abatement in the sector. The geographical scope of the storylines is Germany and its electrical neighbors.[81] The time horizon of the study is 2017 to 2050.

The goal of the scenario process was to translate one or more storylines into a quantitative scenario. The qualitative part of the scenario process was designed and executed by KIT ITAS. Quantitative modeling was performed at FfE. To allow the possibility of a structured combined scenario process, qualitative scenario creation was performed using the CIB method. Quantitative modeling was performed using the FfE model landscape described in section 2. The scenario process was set out to be a loose coupling between qualitative and quantitative scenario processes. It was aimed at translating one or more storylines to quantitative scenarios, as opposed to developing storylines for a predefined quantitative modeling framework.

Semi-annual research partner meetings presented the main points of iteration between the qualitative scenario team at KIT ITAS and the quantitative modeling team at FfE. The meetings were used to exchange information about and discuss the status quo of the qualitative and quantitative processes (e.g., exchange information about descriptors and parameters used). Ultimately, the processes of quantitative modeling and storyline development can be characterized as interdependent, but not closely coordinated. Based on the classification provided in [124], the combined scenario process in eXtremOS can be described as having a medium degree of integration.[82] This results from the fact that the qualitative and quantitative processes were linked by regular meetings, but performed by two different institutions and teams.

In this sense, it is noteworthy that the prevailing opinion expressed by authors of socio-technical scenario literature is that "(…) a very strict coupling can do as much harm as a very loose coupling." [7, p. 1737] They argue that very loose coupling can lead to inconsistencies between qualitative and quantitative scenarios by leaving too much room for interpretation during scenario quantification, whereas overly strong coupling can result in an abundance of compromises between storyline and quantitative scenario generation, potentially leading to a loss of specific knowledge in one of the two areas. This in turn means that consistency between quantitative and qualitative scenarios is important but should not be forced at all cost. For example: storylines might fall short of capturing complex technological boundaries, such as the potential of circular economy measures to facilitate the expansion of secondary process routes in aluminum and steel production. In this example the storyline might assume a strong circular economy. Nevertheless, quantitative modeling must respect the prevailing state of research with respect to technical constraints.

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[81] All countries with existing or planned line transfer capacities to and from Germany: Austria, Switzerland, Italy, France, United Kingdom, Norway, Sweden, Belgium, Netherlands, Denmark, Poland, Czech Republic, Slovakia, Slovenia, and Hungary.

[82] Low integration exists if context scenarios are solely an "add-on" to quantitative modeling. High integration is reached when the CIB delivers results which are explicitly tailored to the demands of the quantitative model landscape [124].

5.2.2 Qualitative Scenario Construction

The CIB matrix developed in the project eXtremOS serves as input for the combined scenario process. Using CIB for the combined scenario process allowed the quantitative modeling team to trace the basic assumptions behind the developed storylines. Furthermore, it provided the starting point of the FWV procedure, which builds on the structured scenario approach using descriptors and trends. KIT ITAS developed scenarios for each region in eXtremOS: Germany, Nordic countries, Southwestern Europe and Central-Eastern Europe [133]. Descriptors and trends were identified based on literature research and internal brainstorming at KIT ITAS. Subsequently, the list was validated through an online questionnaire as well as expert interviews. For each region, a participatory approach consisting of international expert interviews, workshops and online surveys was followed to derive the respective CIB matrices. A set of 23 consistent scenarios was identified, which were further divided into three scenario clusters. For each scenario cluster one storyline was developed [133]:

- S1 – A tough government with climate ambitions in a fragmented Europe (based on ten scenarios)
- S2 – No climate target in a fragmented Europe (based on seven scenarios)
- S3 – Together towards a better world (based on six scenarios)

For this dissertation, storylines S2 and S3 were selected to display the quantification procedure. Furthermore, the slight regional differences in S2 and S3 were consolidated to provide European storylines for demonstrating the FWV procedure. The resulting scenarios have been re-named to avoid confusion with the original storylines.[83]

S2 is renamed to *quEU*. The name quEU is short for *quit EU*, thereby referencing one of the main triggers of the described scenario developments – the dissolving of the EU. QuEU is a scenario in which no climate targets exist. Figure 29 shows the descriptors and trends for the quEU scenario, including a qualitative interpretation of the descriptor state compared to the status quo (i.e., year 2020).

The scenario describes a sociopolitical setting, in which further countries, besides the United Kingdom, exit the European Union. In addition, nationalist politicians gain influence in several European countries and society perceives that the costs of containing climate change outweigh the benefits. These developments result in the neglect of climate targets. Furthermore, availability of public and private funding for renewable technologies is not expanded compared to today's level. In particular, research and development funding for fuel substitution technologies, beyond the current trend, is not supported. The scenario characterizes a geopolitical setting in which currently visible efforts to improve social equality and welfare fall victim to pure economic competition, in the sense of *homo economicus*. This means climate friendly technologies could be adopted if they were cost competitive. Efforts to accelerate their development however do not go beyond the current state.

[83] Scenario summaries are provided below. For elaborate storyline descriptions confer [133].

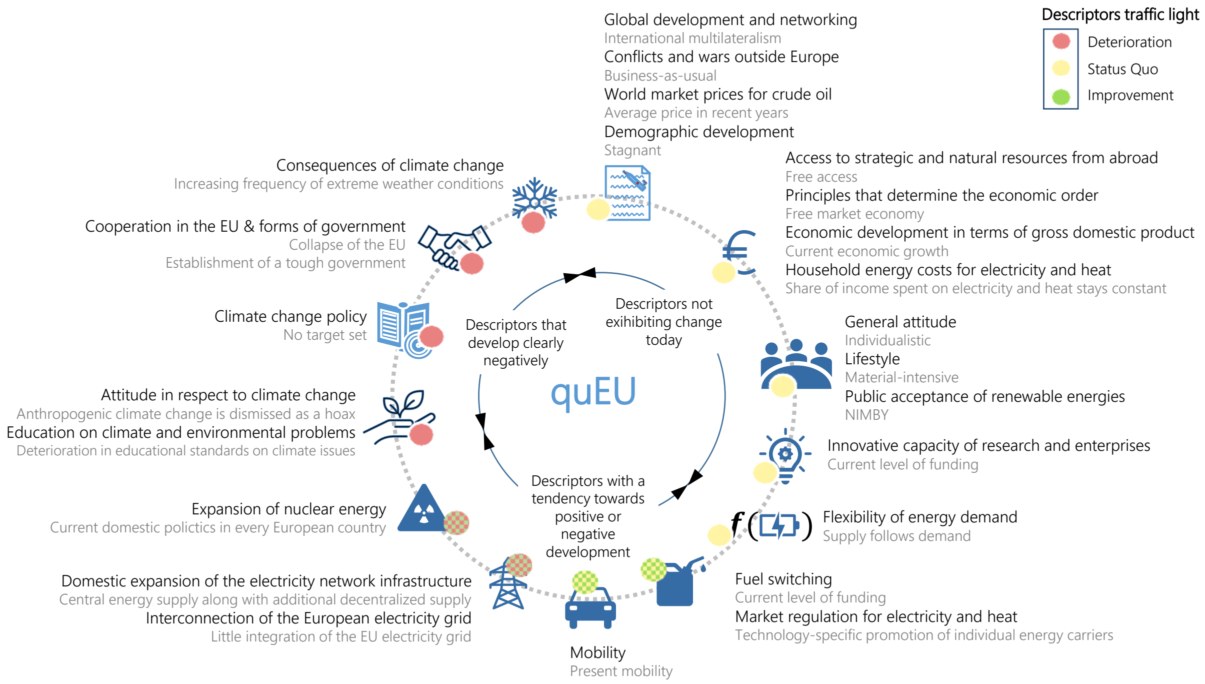


Figure 29: quEU scenario descriptors and trends[84]

S3 is renamed to *solidEU*. The name solidEU is short for *solidarity in the EU*, thereby referencing one of the main triggers of the described scenario developments. SolidEU is a climate protection scenario in which 95 % GHG emission reduction with respect to 1990 levels is reached by 2050 in the EU27+3. National, sectoral and 2030 goals are not considered in solidEU. Figure 30 shows the descriptors and trends for the solidEU scenario, including a qualitative interpretation of the descriptor state compared to the status quo.

The scenario describes a sociopolitical setting characterized by cooperation and a stronger integration of the European Union, with a strengthened participatory democracy [133]. Solidarity and the resulting participative governance are driven by the common understanding that climate change is anthropogenic and poses a serious threat to personal prosperity. This pioneers an ambitious climate policy, supported by the collective goal of deep greenhouse gas reduction at both governmental and societal levels. Consequently, the EU will create a solid national policy framework. The countries which currently have more organized national policies/goals will adapt these to the EU framework. There will be regulations on trade of various resources to implement environmental standards, promote the use of locally available resources, protect sensitive ecosystems, and avoid social conflicts. Intensification of renewables will be promoted by funding research and development as well as technology infrastructure. Moreover, society will work in solidarity for climate protection, triggering lifestyle changes via increased climate awareness. Therefore, people become conscious about their consumption, switching to products with a low carbon footprint. Hence, there will be a new economic order supporting circular economies and reducing consumption of primary resources. Economic growth continues or slows depending on the country. Furthermore, integration of variable renewable energy sources between EU member states is supported with demand-side management.

[84] Own illustration based on the S2 storyline in [133].

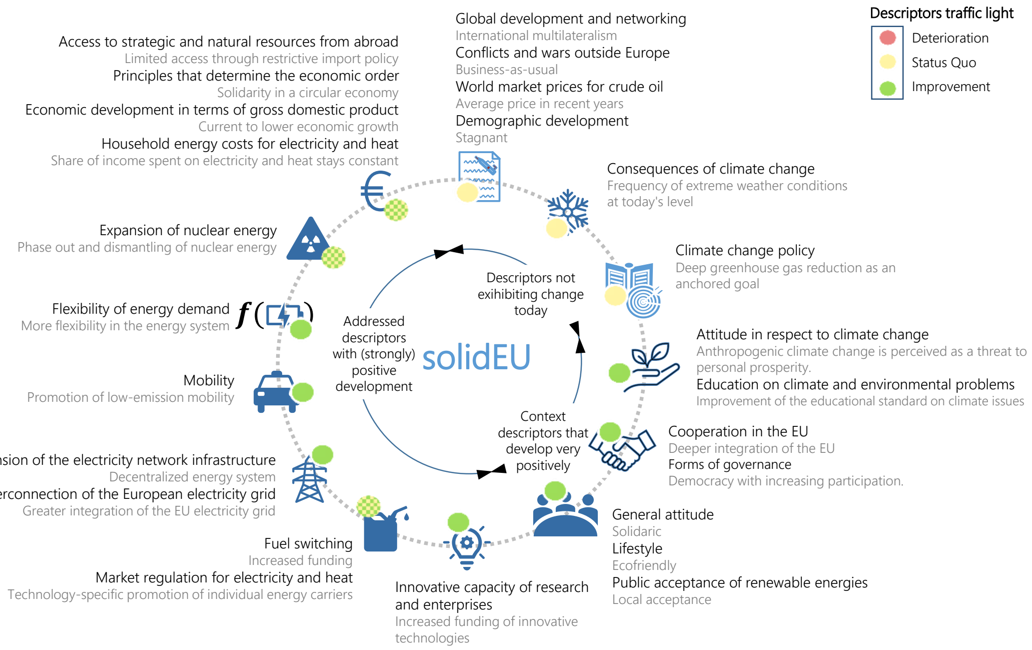


Figure 30: solidEU scenario descriptors and trends[85]

The quEU and solidEU cross-impact matrices and scenario storylines are matched with SmInd EU model parameters in the following section.

5.2.3 From Word to Value

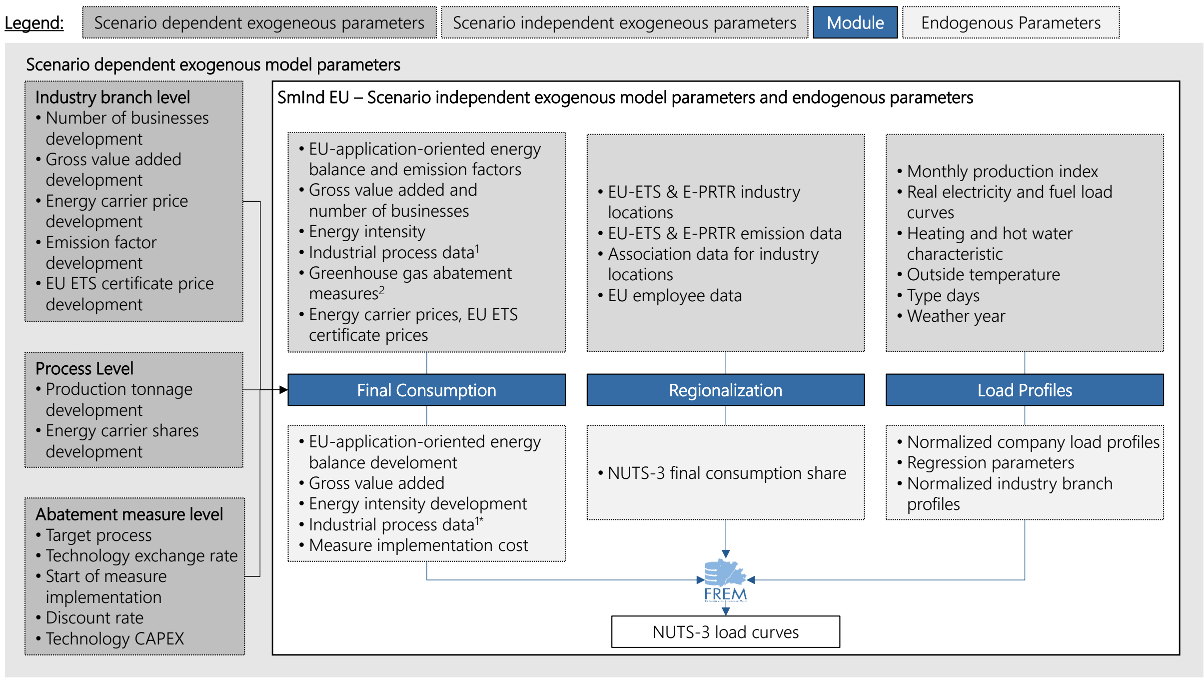
In this step the storylines described in the previous section are connected to SmInd EU, to combine qualitative and quantitative modeling.

Visualization of Model-Landscape and Identification of Exogenous Parameters

Step one in the FWV procedure entails the mapping of all modules and parameters for the tool chain used to derive the quantitative scenarios. Figure 1 in section 2 shows the eXtremOS model landscape including modeling interconnections. The four end-use sector models are connected to a set of supply-side models via so-called energy carrier tracks [13]. The figure shows that from the perspective of the eXtremOS model landscape the sectoral FC is a model endogenous parameter. When assuming the supply-side model perspective alone, FC is model landscape exogenous. From the perspective of SmInd EU, FC is a model endogenous parameter. This shows that the selected model balancing area influences which model parameters can be considered mexP. Furthermore, Figure 1 shows that SmInd EU is independent of inputs from other models. Consequently, parameters which are model exogenous for SmInd EU are also mexPs from the perspective of the entire eXtremOS model landscape.

Figure 31 shows the SmInd EU model overview including the full set of scenario dependent and independent mexPs as well as menPs. Since SmInd EU calculations commence in the base-year 2017, several mexPs are assigned a fixed historical value (scenario independent mexP) and only their development is considered scenario dependent.

[85] Own illustration based on the S3 storyline in [133].



[1] Production tonnages*; Process lifetime; Energy carrier shares*; Specific fuel, electricity and feedstock consumption*; Specific process emissions*; Applications per process
[2] Fixed operating technology cost; Application factor; Technology lifetime; Specific electricity savings; Specific fuel savings; Utilization factor

Figure 31: SmInd EU model landscape including parameter classification

On the industry branch level, the growth rate for the number of businesses and gross value added as well as the development of energy carrier prices, emission factors and EU ETS certificate prices are scenario dependent mexPs. Each of these parameters is quantified including the base year 2017. The FEC and GVA development at industry branch level are model endogenous. This also applies to the energy intensity and its development, which results from future GVA and FEC.

On the process level, scenario dependent mexPs are the production tonnage and energy carrier share development, since both parameters can be affected by CO_2 abatement measure implementation. Therefore, their initial starting values are scenario independent mexPs, but the final result is subject to endogenous model developments. The technical process parameters processing lifetime and process application areas (e.g., temperature level) are scenario independent mexPs. Model simulation runs ultimately result in endogenous parameter variations for the specific fuel, electricity, and feedstock consumption as well as the specific process emissions.

At the abatement measure level, the target process, technology exchange rate, start of measure implementation, end of measure implementation, technology CAPEX and discount rate are scenario dependent mexPs. The technical parameters application factor, technology lifetime, specific electricity savings, specific fuel savings, utilization factor as well as the cost parameter fixed operating technology cost are considered scenario independent mexPs.

Across all levels of the final consumption module, the menPs most relevant for holistic evaluation of CO_2 abatement measures are the development of the EU energy carrier and application balance as well as the measure implementation costs.

The regionalization and load profile module do not exhibit scenario dependent mexP in this dissertation. Consequently, these modules are scenario independent. In the following section the identified scenario dependent mexPs are matched with descriptors from the CIB matrix.

Development of Descriptor-Parameter Matrix

The aim of the DPM is to show all links between parameters and descriptors. Figure 32 shows the result of the identification procedure for SmInd EU and the CIB matrix which was used to derive quEU and solidEU.

The DPM for SmInd EU shows that 10 out of 12 scenario dependent model exogenous parameters are linked to eight out of 25 scenario descriptors. Hereby, *climate change policy, world market prices for oil* and *economic development - GDP* are directly linked to SmInd EU parameters, while the remaining descriptors exhibit weak links. Seventeen of the 25 defined descriptors are not visualized since they remain unconnected to SmInd EU model parameters. Below, the descriptor-parameter links are described in detail.

Legend: Direct link | Weak link | Not linked

Cluster			Political				Societal	Economic		Energy
Descriptor			Climate change policy	World market prices for oil	Innovative capacity	Fuel switching	Attitude in respect to climate change	Economic development - GDP	Economic order	Energy market regulation
Production tonnage development	% p.a.	1/0						yes	yes	
Energy carrier shares development	% p.a.	1			yes	yes				
Gross value added development	% p.a.	1						yes	yes	
Number of businesses development	% p.a.	1						yes		
Technology CAPEX	€ / unit	1								
Technology exchange rate	% p.a.	1			yes	yes				
Start of measure implementation	#	1			yes	yes	yes			
Target process	#	1			yes	yes			yes	yes
Energy carrier prices	ct / kWh	1/2		yes						
Emission factors	kg CO2 / kWh	1/2	yes							
EU ETS certificate price	€ / t CO2	1/2	yes							
Interest rate	%	1								

Figure 32: Descriptor-parameter-matrix showing descriptors linked to SmInd EU mexP

The **climate change policy** descriptor is linked directly to the *EU ETS certificate price* parameter. The descriptor addresses policies and climate protection targets. As a policy instrument to control emission reduction in Europe, the EU ETS certificate price is consequently directly affected by the descriptor. In addition, the *climate change policy* descriptor is affected by a variety of other descriptors such as *innovative capacity* or *fuel switching* [134]. To enable a deeper understanding of the sociopolitical interdependencies between descriptors and their effect on model parameters, descriptor-parameter links are drawn as closely as possible to the root-cause descriptor. For example: *climate change policy* impacts the *technology exchange rate* of abatement technologies. However, this link is not shown in the DPM, since the descriptors *innovative capacity* and *fuel switching*, which are causal to the *climate change policy* descriptor, exhibit a stronger link to this parameter.[86]

The **world market prices for oil** descriptor is directly linked to the *energy carrier prices* parameter for fuel oil. In absence of further energy price descriptors, it is considered a proxy for fossil fuel price development.

The descriptors **innovative capacity** and **fuel switching** possess weak links to the abatement measure parameters *energy carrier shares development, technology exchange rate*, *start of measure implementation* and *target process*. Both descriptors describe the availability of public and private funding for the development and implementation of technologies required for deep CO_2 emission cuts. Consequently, these descriptors influence the type of measures available for implementation, the transformation speed as well as the earliest possible year of implementation.

The **education** and **attitude towards climate change** descriptors are weakly connected to the *start of measure implementation*.[87] In quEU worsening educational standards cause society to deny its responsibility for climate change. In solidEU the opposite is the case and society accepts the anthropogenic nature of climate change. In solidEU this acceptance for societies' responsibility for climate change triggers acceptance for renewable technologies, which in turn positively impacts the *fuel switch* and *innovative capacity* descriptors, thereby enhancing their effects on model parameters. Even though *attitude towards climate change* and *education* are prior to *fuel switch* and *innovative capacity* descriptors in the causal scenario chain, a connection to the *measure start* parameter is drawn. This results from the assumption that social acceptance and knowledge act as additional accelerants with respect to measure implementation. In

[86] Refer [16] for a causal loop diagram showing the causal links between descriptors.
[87] Hereby the *education* descriptor directly impacts *attitude towards climate change.*

quEU this argument is reversed, and it is assumed that *attitude towards climate change* and *education* further hamper measure implementation.

The **economic development – GDP** descriptor has a direct link to the parameters *gross value added* and *production tonnage development* as well as a weak link to the *number of businesses development*. The connection to these parameters results from the causal connection between GDP, gross value added and the production index [30]. Furthermore, it is assumed that the economic output is also connected to the number of businesses in a country.

The **economic order** exhibits weak links to the *production tonnage*, g*ross value-added development,* and *target process* parameters. In quEU the status quo of a free competition in a rule-based market is continued. In solid EU the *economic order* changes to *solidarity in a circular economy*. It is assumed that this switch impacts the GVA and production tonnage development and that the target process for process substitution measures is affected due to higher scrap availabilities as a result of a stronger circular economy.

Energy market regulation is tied weakly to the abatement technology parameter *target process.* In both context scenarios the status quo trend *technology specific promotion of individual energy carriers* is assumed. Technology specific market regulation can both foster and hamper process substitution depending on the type of promotion.

Despite the described connections between descriptors and parameters, 17 of the 25 defined descriptors remain unconnected to SmInd EU model parameters. This is a result of the framing and aim of the context scenarios, which is the holistic description of the energy system transformation (cf. scenario description in section 5.2.2). This comprehensive approach comes at the cost of sectoral detail, which becomes especially visible in the complex and heterogenous industry sector. When considering mexP from the entire eXtremOS model landscape (cf. Figure 1) only five scenario descriptors remain unaddressed. The number of unaddressed descriptors from the perspective of SmInd EU indicates that insufficient context exists to achieve the full and traceable quantification of the industrial energy transition in quEU and solidEU. This is also reflected by the unaddressed model exogenous cost parameters t*echnology CAPEX* and *discount rate*. The descriptors i*nnovative capacity* and *fuel switching* provide a qualitative indication concerning the degree to which incentives for measure implementation are provided to stakeholders. However, a causal (weak) link to the technology CAPEX and discount rates cannot be established. Consequently, additional research is required to supplement the solidEU storyline with information required to quantify the industry branch specific energy transition.

Parameter Quantification for quEU and solidEU

The quantification of parameters completes the FWV procedure. The analysis in the previous section shows that weak links dominate the SmInd EU DPM. In addition, a variety of descriptors and scenario dependent mexPs remain unaddressed, resulting in a demand for additional analysis to fully frame and quantify the European industrial transformation in quEU and solidEU. In this section, parameters based on the DPM and informed by literature research are quantified. Industry specific transformation pathways for quEU and solidEU are discussed in section 5.3.

The activity parameters **production tonnage, gross value added,** and **number of businesses development** are addressed by the *economic development* and *economic order* descriptors. For quEU current economic growth and for solidEU current to lower economic growth are assumed in the context scenarios. As described in 4.1.2, long-term country and industry branch specific economic development data from the EU reference scenario serves as input data for this thesis [100]. With an EU-wide average growth rate of approximately 1 % p.a., from 2020 to 2050, this data in combination with the consistent production tonnage development from [52] satisfies the demands of the context scenarios. To the best of the author's knowledge further consistent GVA and production data sets allowing a differentiation of economic data between quEU and solidEU are not publicly available.[88] Figure 33 depicts the exogenous production development assumed in both scenarios.

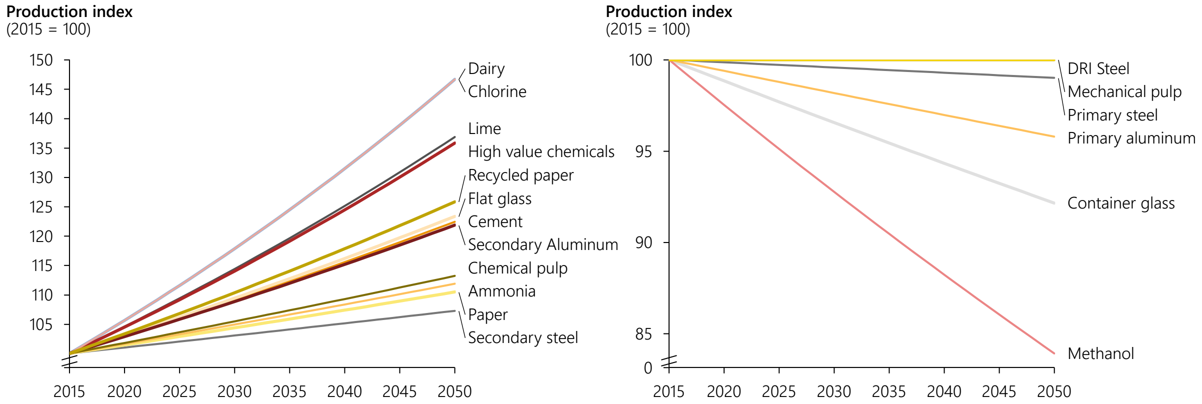


Figure 33: Exogenous production tonnage index for processes modeled bottom-up, 2015 - 2050[89]

Since there are no known and consistent projections with respect to the number of businesses, it is held constant in both scenarios.[90] In addition to the *economic development* descriptor, the mentioned parameters are addressed by the *economic order* descriptor. The latter assumes the trend *free competition in a rule-based market* in quEU and *solidarity in a circular economy* in solidEU. The shift towards a more circular economy in solidEU is reflected by a shift in production tonnages towards recycling process routes in steel and aluminum production. The latter is modelled mainly as a CO_2 abatement measure but is also to some extent reflected in the exogenous production tonnage development in Figure 33.

The energy carrier price parameter for fuel oil is directly linked to the *world market prices for oil* descriptor. While the descriptor trends include indicative values for the oil price development, they are still insufficient for satisfying the data demand of SmInd EU. Despite the direct link, descriptor trends and parameter values are therefore not identical and further assumptions are required to quantify the oil price. In both quEU and solidEU the storyline assumes that world market prices for oil remain at a similar level compared to today. This however, is not in line with the oil price forecasts in reliable studies such as [100, 135], in which global increases in oil demand lead to rising prices. This inconsistency exemplifies how holistic qualitative scenarios, which rely on the input of interviewees, sometimes lack detailed knowledge with respect to some descriptors. Consequently, the oil price assumption is interpreted as "the development is assumed to continue as expected under current policy influence." Building on country-specific starting values derived from [136], the oil price trajectory for both scenarios is derived based on the IEA World Energy Outlook New Policies scenario [135]. The latter builds on the assumption that existing policies are implemented successfully and are therefore consistent to the refined descriptor trend.

In absence of further descriptors supporting the quantification of the remaining energy carrier price parameters, several additional assumptions and references are required. Where possible, energy carrier prices are differentiated by country, cost perspective and scenario.[91] The described aspects concerning energy carrier prices are based on the master's thesis [137], which was supervised by the author of this dissertation. Energy carrier prices used for the cost evaluation in section 7 originate either from exogenous literature sources or simulations with the energy system model ISAaR and the gas market model MInGa

[88] Deriving own economic projections is not in scope of this thesis, as this would require an economic model which can map complex input-output relationships. In [52] further European production tonnage development scenarios are listed, but excluding consistent GVA scenarios.
[89] Own illustration based on data from [52].
[90] The effect of this assumption on modeling results is negligible since the number of businesses is only relevant as a specific activity figure for the implementation of cross-sectional measures and is not connected to fundamental FEC development.
[91] Please cf. [137] for a comprehensive list of energy carrier prices and emission factors by country and year.

[6, 13, 14]. As described in section 2 the energy system model ISAaR and gas market model MInGa receive final energy consumption as exogenous model input. Subsequently, the cost optimal energy carrier procurement is calculated, thereby providing the basis for calculating energy carrier prices and emission factors. These are then used as input for cost and emission calculations in SmInd EU.

Table 13: Energy carrier and feedstock cost and price assumptions and references

<table>
<tr><th>Energy carrier / Feedstock</th><th>Scenario dependent?</th><th>Origin</th><th>Price or cost & perspective</th><th>Regional resolution</th><th>Temporal resolution</th><th>Reference</th></tr>
<tr><td>Biomass, Lignite, Coke, RES fuel, non-RES waste</td><td rowspan="4">No, except biomass</td><td rowspan="3">Literature-based</td><td rowspan="3">Investor price</td><td rowspan="2">EU</td><td rowspan="3">Annual</td><td>[52]</td></tr>
<tr><td>Hard coal, Peat</td><td>[6, 52]</td></tr>
<tr><td>Fuel oil/Naphtha, Other fossil fuels</td><td>Country specific</td><td>[52, 73, 136]</td></tr>
<tr><td>Coke oven gas & blast furnace gas</td><td colspan="5">Treated as costless waste gas</td></tr>
<tr><td>Methane</td><td rowspan="5">Yes</td><td rowspan="5">Model simulations & literature[92]</td><td rowspan="2">Investor & System price</td><td rowspan="2">Country specific</td><td>Daily</td><td>[16, 138]</td></tr>
<tr><td>Electricity</td><td rowspan="4">Hourly</td><td>[16, 139]</td></tr>
<tr><td>Hydrogen</td><td rowspan="2">Investor price & system cost</td><td rowspan="3">EU</td><td>[16, 138]</td></tr>
<tr><td>Synthetic methane</td><td rowspan="2">[16]</td></tr>
<tr><td>Synthetic fuels</td><td>System cost</td></tr>
</table>

The table shows the different levels of detail for energy carriers used in SmInd EU. The prices for biomass, lignite, coke, renewable energy source fuels (RES fuels), non-renewable waste (non-RES waste), hard coal, and peat are based on [52]. [52] derives energy carrier price developments consistent to the EU Reference Scenario and World Energy Outlook [100, 135]. GVA, production tonnage and energy carrier price developments are consequently consistent. Average EU prices as well as identical system and investor prices are assumed for these energy carriers. This results from a lack of country specific data regarding the energy carrier price development and share of taxes, levies, and surcharges. The primary steel making waste gases coke oven and blast furnace gas are treated as costless waste products. System costs and prices for fossil and synthetic methane, electricity, hydrogen, and other SynFuels including naphtha and MeOH are derived based on output of the energy system model ISAaR and additional downstream assumptions. Hereby, a differentiation between price and cost is made. For electricity and natural gas, system prices based on the merit-order procedure result from ISAaR and MInGa, respectively. For hydrogen, as well as synthetic methane and oil, levelized system costs are calculated based on hourly electricity prices and technology cost data. Subsequently taxes, levies and surcharges are added to the system costs and prices to derive investor prices.

Resulting from ISAaR model simulations, natural gas can be blended with synthetic methane and fuel oil/naphtha with chemically equivalent SynFuels, ultimately affecting the energy carrier price development.[93] In quEU, which is not a climate protection scenario, this does not occur. In solidEU, which is a climate protection scenario, 5 % green synthetic methane is blended with natural gas by 2045. By 2050 natural gas is fully substituted by green synthetic methane, of which 80 % is imported to the EU. This is reflected by the natural gas system price increase from ~15 €/MWh to ~90 €/MWh from 2045 to 2050 shown in Figure 34. In solidEU fuel oil is fully replaced with emission-free SynFuels by 2050. Compared to

[92] Taxes, levies and surcharges based on 2017-2019 average and assumed constant until 2050. For electricity and natural gas industry branch specific differentiations are made based on the allocation in [18]. Taxes, levies, and surcharges for natural gas are assumed for synthetic methane and hydrogen. For synthetic fuels system cost and investor price are not differentiated, since taxes, levies, and surcharges for fuel oil (which could be used as indicative values) are not available.

[93] Energy carrier prices for naphtha and fuel oil are not differentiated due to historically similar prices [52]. Furthermore, the author is aware of the fact that natural gas has varying shares of methane. For simplicity in model calculations, it is however assumed that synthetic methane can be blended with and can substitute natural gas.

the 2050 fuel oil prices in quEU, emission-free SynFuel is less expensive in solidEU 2050 (98 €/MWh). Hereby it is important to note that quEU and solidEU present two entirely separate scenario worlds. The increase in fuel oil prices in quEU results from the assumption that global fuel oil demand increases further [135]. In solidEU, the price trajectory differs from quEU as of 2030, since the demand for fuel oil decreases and SynFuels are blended with fuel oil.[94] Figure 34 summarizes the energy carrier price development.

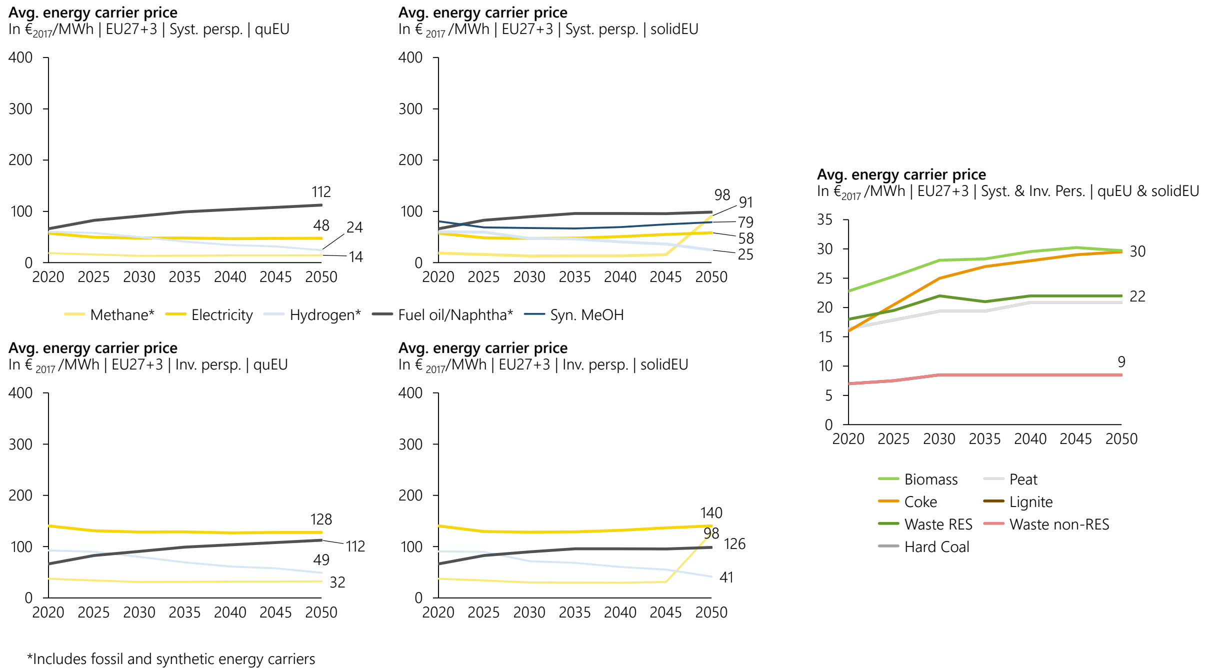


Figure 34: Weighted average European energy carrier cost and price development, 2020 to 2050[95]

In both quEU and solidEU hydrogen system and thereby investor costs decrease until 2050. ISAaR calculates the cost optimal annual procurement of hydrogen, which is either produced via steam reforming or electrolysis. In quEU and solidEU hydrogen imports to the EU are excluded by assumption. Consequently, the entire demand is covered by domestic EU production. Unlimited hydrogen trade between countries is allowed. A hydrogen infrastructure is modeled implicitly by assuming transport losses of 0.5 %/100km. Furthermore, an infinite European hydrogen storage system is assumed, which is charged and discharged without losses and cost throughout the year. In the cost optimization, these assumptions lead to a strong seasonal hydrogen production profile. Hydrogen is mainly produced (and stored) in times of low electricity prices (i.e., March to October), which explains how hydrogen prices in Figure 34 can drop below average European electricity prices. For the cost evaluation in this thesis current natural gas taxes, levies and surcharges are assumed for the hydrogen investor price.

[94] Modeling synthetic methane and fuel in ISAaR: green synthetic methane is imported at ~100 €/MWh in 2050 [73], while average levelized production costs in Europe are ~52 €/MWh in 2050. The import share of 80 % of green synthetic methane is due to a daily load coverage constraint for gas in combination with a high share of gas consumption in times where electricity demand is comparably high (October to March). During these times levelized costs of green synthetic methane production are not cost competitive in comparison to imports. For synthetic fuels an annual load condition is implemented. Both import and the levelized cost of green synthetic fuel production in Europe are ~100 €/MWh in 2050. By 2050 70 % is imported [140].

[95] Since the starting year of simulations is 2017, 2020 values are simulation and interpolation results. Prices are excluding EU ETS certificate price. Prices are average prices for the EU27+3 weighted by total energy and feedstock consumption for each energy carrier and by country. In the cost calculation they are differentiated by country and industry branch where possible. MeOH feedstock prices are not linked to MeOH production in SmInd EU. It is assumed, that MeOH feedstock for MTO/MTA processes is imported. To avoid confusion with the purely fossil energy carrier natural gas, the energy carrier is named methane in diagrams where the substitution of natural gas through synthetic methane is relevant.

Electricity prices in quEU and solidEU remain stable over time. Nevertheless, taxes, levies and surcharges lead to high average European investor prices for the industry sector. It is important to note that industry branch specific electricity prices are used for the measure and transformation pathway cost calculations in section 7.

The **EU ETS certificate price** parameter is directly linked to the *climate change policy* descriptor. The descriptor trends assumed in quEU and solidEU are *no target value* and *current EU climate change policy*, respectively. For quEU the assumption is made that despite the sociopolitical reluctance to climate targets, current emission reduction policies are continued. This is consistent to the *innovative capacity* and *fuel switching* descriptors, in which current technology funding levels are sustained. Consequently, the EU ETS remains in place and a price trajectory based on the National Trends scenario in the Ten-Year Year Network Development Plan is assumed [10]. In solidEU, a higher certificate price trajectory is required to achieve climate targets. In ISAaR, this is modeled implicitly via a GHG-emissions cap [16]. Table 14 shows the respective certificate price developments.

Table 14: EU ETS certificate price development in quEU and solidEU[96]

	2020	2030	2040	2050
quEU	30	42	64	85
solidEU	30	48	90	236

Emission factors for the secondary energy carriers electricity, hydrogen, synthetic methane, and synthetic fuels are weakly linked to the *climate change policy* descriptor and are a result of ISAaR model simulations. The weak link results from the influence of the ISAaR emission cap on the operation and expansion of power plants. While ISAaR minimizes costs for operation and expansion of the power sector, it does so under a GHG emission constraint. Ambitious climate policy consequently influences the composition of the power sector, thereby influencing emission factors of secondary energy carriers. Secondary emission factors are country specific. Electricity and hydrogen EMF are hourly, synthetic methane daily and synthetic fuels annual values. Emission factors for primary energy carriers (e.g. coal, fossil fuel oil, natural gas) are taken from national inventory reports of the respective countries: e.g. [26] for Germany. Biomass is treated as sustainable biomass and therefore balanced with net-zero emissions. Figure 35 shows the emission factors for quEU and solidEU.

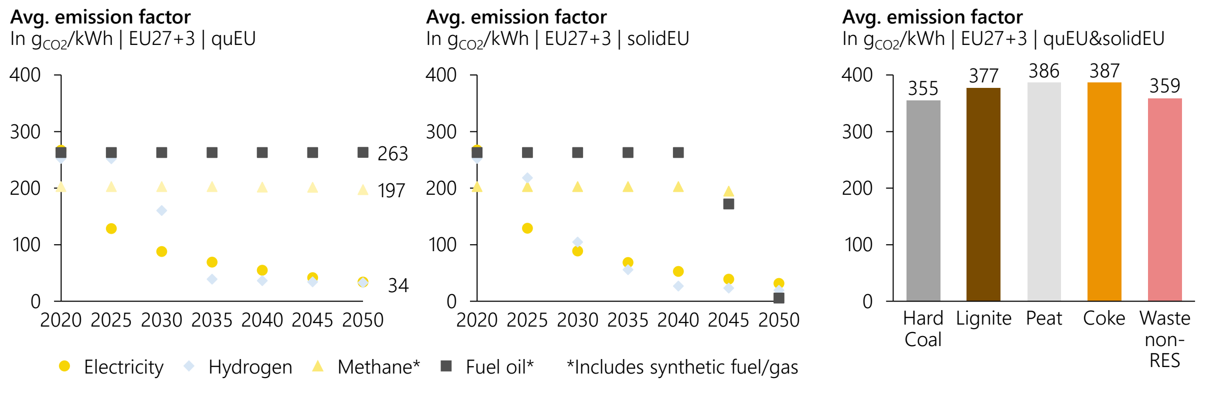


Figure 35: Weighted average European emission factors in quEU and solidEU, 2020 to 2050[97]

The cost parameters **technology CAPEX** and **discount rate** are not addressed by qualitative scenario descriptors. Both parameters are considered scenario independent. Discount rates differ depending on the

[96] Since emission targets are modeled via a GHG cap, prices are a result of model calculations in solidEU. For 2050 CO_2 price results are not interpretable. For cost evaluations in this thesis values for 2045 are assumed for 2050.
[97] Biomass and renewable fuels are assumed to be carbon neutral.

cost perspective (cf. section 6) [6, 141]. Based on the arguments detailed in [6], the discount rate for the investor perspective is set to 10.5 % and the system perspective to 3 %. As described in section 3.3, the technology CAPEX is measure-specific and based on expert validated literature data.

The abatement measure implementation parameters **start of measure implementation, end of measure implementation, target process, energy carrier shares development** and **technology exchange rate** are linked to five different descriptors in the clusters political, social, energy and economic. Despite these links, the context scenario fails to provide sufficient detail to perform the industry branch, process, and abatement measure specific quantification of parameters. Hence, the context scenarios are expanded by further literature analysis and expert opinions in section 5.3.

5.2.4 Simulation and Usage

In the context of this dissertation simulation results for the quEU and solidEU scenarios serve the purpose of evaluating European industrial transformation pathways as well as individual CO_2 abatement measures. To do so, first, SmInd EU scenario results are used as input data for the energy system model ISAaR. As explained in section 4 the SmInd EU simulation runs yield hourly industrial final consumption data for all NUTS-3 regions in the EU27+3. In combination with input data sets from the transport, tertiary, and household FEC models, ISAaR is provided a holistic input data set for both scenarios. Through linear optimization, the energy system model ISAaR then determines the cost-optimal European unit dispatch and expansion for quEU and solidEU. A GHG emission reduction constraint is deployed in solidEU, but not in quEU. Selected results for the energy supply-side in quEU and solidEU can be viewed in the interactive ISAaR dashboard, but are not elaborated further in this dissertation [140]. Based on ISAaR simulation results the scenario-dependent emission factors as well as costs and prices of energy carriers discussed in section 5.2.3 are calculated. The latter build the basis for analyzing transformation pathway costs and emissions. Furthermore, they allow for the evaluation of individual CO_2 abatement measures in the context of the quEU and solidEU scenario worlds.

5.3 Transformation Pathways by Industry Branch

The FWV procedure in section 5.2.3 shows that additional context is required to allow the traceable quantification of the industrial transformation pathways in quEU and solidEU. Hence, European transformation strategies for all industry branches and processes modeled bottom-up are defined. Transformation strategies are not differentiated by country; nevertheless, country-specific transformation pathways result from scenario simulations since country details on industry branch and process level are considered. Based on the description of abatement strategies provided in section 3.3.1 three basic principles for measure implementation are applied to all industry branches and processes:

1. Efficiency first
2. Electrification before biomass fuel switch or carbon capture
3. Efficient electrification (i.e., direct before indirect electrification)

Figure 36 summarizes the key measure implementation parameters for quEU and solidEU.[98] It shows that measures solely from the energy and material efficiency cluster are implemented in quEU. This assumption is based on the context descriptors *innovative capacity, fuel switch measures* and e*conomic growth - GDP*.

The descriptor trends for *innovative capacity* and *fuel switch measures* lead to the current level of funding availability for innovative technologies and fuel switch measures in quEU. To date, the current level of private and public funding has not triggered the widespread adoption of fuel switch or other innovative abatement measures in the industry sector. This is a result of low TRLs as well as additional lifecycle costs incurred to industrial actors who implement fuel switch and carbon capture measures [37, 74]. Hence, the

[98] Confer appendix 9.5 for the full measure list.

study overview in [1] as well as the results of [6, 18, 82, 86, 89] show that these measures cause additional costs for industrial actors and are predominantly phased in because of high CO_2 certificate prices in deep emission reduction scenarios. In the quEU scenario, funds are insufficient for incentivizing fuel switch and other innovative industrial abatement measures. Furthermore, sufficiency measures are excluded from the scenario as the industrial gross value added grows consistently throughout the time frame of the scenario.

The main drivers for the development of industrial FC in the quEU scenario are economic growth and efficiency improvements. As described in section 3.3 efficiency measures are sub-divided into process, cross-sectional, and proxy measures. Efficiency measures are implemented in all industry branches. The starting year of measure implementation is based on the technology readiness level. CST measures which are characterized by low technical complexity are implemented as of 2021. More complex process efficiency measures are implemented 2030 or later. In both cases the technology exchange rate is tied to the technical lifetime of the respective technologies. Since fuel switch measures are not relevant in quEU, the mexP *measure start* is not quantified.

	CO_2 Abatement Measure	**Reference Process / app.**	**Earliest Measure Start**		**Exchange rate In %/a**	**Applicatio factor In %**
			quEU	**solidEU**		
Efficiency	Process efficiency	Process applications	2030	2021	3 – 20	10 – 99
	CST efficiency	CST applications	2021	2021	4 – 100	16 – 99
Fuel substitution (processes)	Electric arc furnace	Primary steel	-	2025	5	Country spec.
	H2-DRI & EAF	Primary steel	-	2025	5	Country spec.
	Methanol-to-Olefins	HVC	-	2025	4	60
	Methanol-to-Aromatics	HVC	-	2025	4	60
	Electrocracker	HVC	-	2040	10	40
	Power-to-Ammonia	Ammonia	-	2025	4	100
	Power-to-Methanol	Methanol	-	2025	4	100
	Multi-fuel & H_2 burners	Cement & lime	-	2030 & 2040	5 & 10	100
	Electrical container glass	Container glass	-	2025	4	100
	Electrical flat glass	Flat glass	-	2025	7	100
	Innovative electrodes**	Primary aluminum	-	2035	10	100
Fuel sub. CSM	Ind. heat pump	HW & PH <100 °C	-	2025	5	100
	Ind. heat pump & electrode boiler	PH 100 °C – 500 °C	-	2025	5	100
	Multi-fuel & H_2 burners	HW & PH	-	2030 & 2040	5 & 10	100
CC	CCS cement / lime	Cement & lime	-	2025	10	100

CSM: Cross-section measure | CC(S): Carbon capture and Storage | CST: Cross-sectional technology | DRI: Directly reduced iron
EAF: Electric arc furnace | HVC: High value chemicals | HW: Heating and hot water | PH: Process heat

Figure 36: CO_2-abatement measure implementation overview for quEU and solidEU

As in the quEU scenario, solidEU builds on the implementation of efficiency measures. In solidEU process efficiency measure implementation commences in 2025, due to the availability of additional funding and high sociopolitical transformation pressure. Nevertheless, the number of implemented technical efficiency measures sinks compared to quEU, since interdependencies with fuel switch measures are considered. These game-changer measures become a viable option since sufficient funding for R&D as well as implementation support is available (cf. Figure 36). The industry branch specific transformation pathways resulting from the sociopolitical setting in solidEU are described in the following sections.

Iron and Steel Production

The solidEU steel transformation pathway is based on the evaluation of current technology reports and steel transformation scenarios [5, 6, 32, 43–46, 52, 82, 90] as well as the transformation pathways in the projects [16, 91], which are based on expert consultations.[99]

In the SolidEU scenario, primary steel is substituted through secondary steel until the upper limit due to scrap availability is reached. This is consistent with the descriptor *economic order* which assumes the trend *solidarity in a circular economy* and is weakly linked to the *target process* parameter in SmInd EU. Considering the upcoming reinvestment cycles and the projected slow increase of scrap availability of 0.9 % p.a. until 2050, secondary route capacity investment commences in 2025 [44]. Despite the scenario setting in solidEU, industrial actors are consequently not expected to undertake “overnight investments”. Hence, investments in the reference technology are expected for the 18 % of European primary steel production capacity due for refurbishment between 2021 and 2025 [5]. As of 2025 a linear capacity exchange rate of 5 % p.a. based on 20-year refurbishment intervals is assumed. Hereby, secondary steel production is not emission free to begin with. Remaining emissions stem from electricity as well as the use of coal as a reduction agent and natural gas to pre-heat the EAF charge. As of 2040 coal and natural gas are substituted through biogenic coal and hydrogen, respectively. By 2050, secondary production is almost entirely emission free except for the electrode burn-off.

Due to the availability of funding for the development and implementation of innovative technologies in solidEU, it is assumed that the H_2-DRI & EAF route achieves a breakthrough. Implementation commences in 2025 with a linear capacity exchange rate of 5 % p.a. Hydrogen is used as a reduction agent as of 2025. Energy consumption for direct reduction is natural gas based until 2040. Between 2040 and 2050 the hydrogen share is increased to 100 %.[100] The resulting steel transformation pathway is depicted in Figure 37.

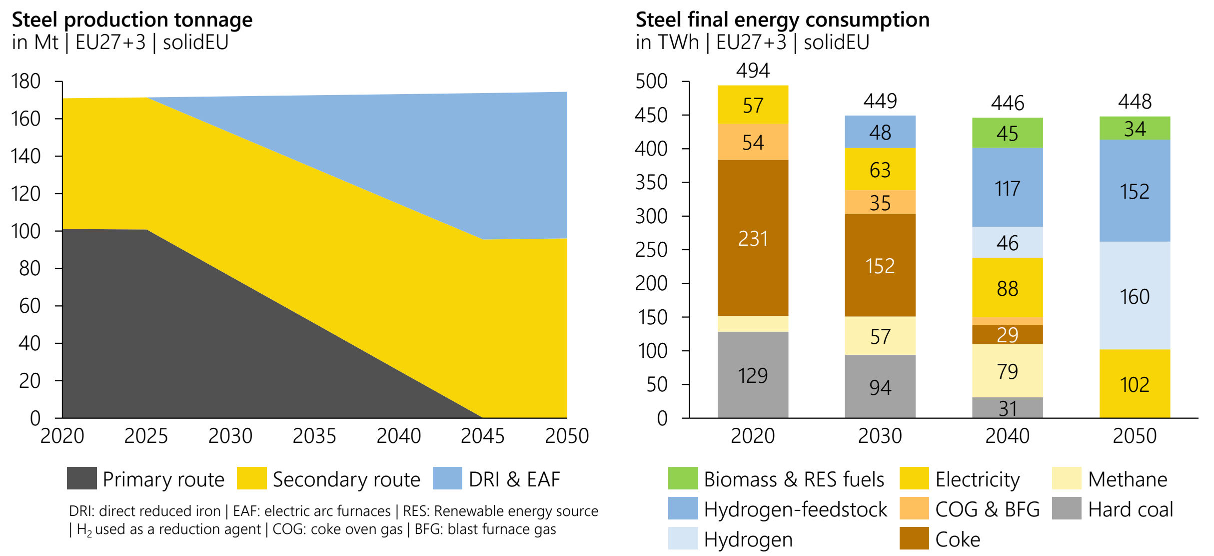


Figure 37: solidEU steel production transformation pathway[101]

[99] The author of this dissertation was part of both project teams. The ongoing project [91] aims at deriving deep decarbonization pathways for the German basic materials industry. The core element of the project is the frequent exchange with basic materials associations and companies, aimed at validating technoeconomic data through process experts.
[100] The use of DRI in existing blast furnaces is another bridging option.
[101] Biomass & RES fuels contain all solid and liquid bio energy carriers incl. RES waste.

The development of production tonnages on the left-hand side of Figure 37 shows that the substitution of primary through secondary steel and DRI steel commences 2025 and is concluded by 2045. Consequently, 25 % of European primary steel production capacity is substituted every five years between 2025 and 2045. Considering that refurbishments can be delayed for a short period of time, the assumed linear replacement is relatively consistent to the estimated reinvestment cycles published in [5]. On the right-hand side of Figure 37 the gradual replacement of the primary production route is reflected by the reduction of coke, hard coal, and COG & BFG consumption between 2020 and 2050. Direct electricity consumption in the European steel industry increases by ~80 % from 57 TWh in 2020 to 102 TWh in 2050. The consumption of energy and feedstock related hydrogen is predominantly driven by the H2-DRI & EAF process route and totals 312 TWh by 2050.[102] Furthermore, 34 TWh of biogenic coal are required as a reduction agent for steel scrap in the EAF.[103] In summary, the European solidEU steel transformation builds on the maximization of secondary and hydrogen-based steel. Prerequisites are a fast technology development to enable the market readiness of industrial scale DRI production by 2025. An immediate and steep increase of hydrogen demand is avoided by using natural gas as an energy source for the EAF until 2040.

Chemical Industry – Ammonia, Olefines, Aromatics, Methanol and Chlorine

The solidEU basic chemical transformation pathways are based on the evaluation of the current chemical industry roadmaps and technology reports [46, 51, 53], industrial transformation scenarios [5, 52], and transformation pathways in the project [91], which are based on expert consultations.[99]

For HVC production, the pathway builds on the MTO, MTA and E-HVC processes. Fifty three percent of European steamcracker capacity with a technical lifetime of 50 years is due for maintenance by 2030 [5]. HVC production can potentially be completely emission free using the E-HVC technology, which is however only available as of 2040.[104] Under the very good technology development circumstances in solidEU, it is expected that MTO and MTA processes are market ready by 2025. It is assumed that for half of the steamcracker capacity (~6 Mt_{HVC} or 13 % of total capacity), which are due for refurbishment between 2020 and 2025, maintenance is conducted as planned [5]. Assuming 25 years until the next major reinvestment cycle, this capacity will be substituted through E-HVC between 2045 and 2050. For the remaining half, it is assumed that only essential repairs and maintenance work is performed, in preparation for the iterative process substitution as of 2025. The steamcracker capacity due for refurbishment between 2040 and 2045 (~7 Mt_{HVC}) as well as after 2050 (~6 Mt_{HVC}) is also substituted by E-HVC. Consequently, 40 % of total steamcracker capacity in 2017 is substituted by E-HVC between 2040 and 2050. The remaining 60 % of capacity is substituted continuously between 2025 and 2050. An abrupt bulk substitution of steamcrackers through MTO and MTA processes is not expected. It is assumed, that industrial actors and politicians anticipate and take measures against a possible surge in hydrogen demand at the beginning of the industrial transformation period.

In solidEU NH_3 production via conventional steam reforming is substituted through the $P2NH_3$ process. The required hydrogen and nitrogen are produced via water electrolysis and air separation, respectively. Process substitution commences in 2025. In absence of data showing the age structure of current steam reforming units a linear capacity exchange rate of 4 % p.a. based on a technology lifetime of steam reforming units of 25 years is assumed. Under these assumptions 2025 poses the latest possible year for the beginning of measure implementation to avoid stranded steam reforming assets until 2050. Hereby, it is important to note that the transition towards $P2NH_3$ is not entirely exogenous since hydrogen procurement is optimized by the energy system model ISAaR. This means that the fuel and feedstock demand for steam reforming as well as the electricity demand for electrolysis result from the optimization in ISAaR. The transformation

[102] Assuming an electrolysis efficiency of 66 % this translates to 473 TWh green electricity demand in 2050. This equates to ~40 % of the total European industrial electricity demand in 2017 [6].

[103] In 2040 bio-coal is used as a reduction agent in primary and secondary steel making. As the primary route is phased out, biomass demand sinks slightly until 2050.

[104] While [5] state 2030 as the earliest possible year of implementation, expert estimates from [91] argue that this will not be possible before 2040.

pathway in SmInd EU solely determines the final energy demand for hydrogen and electricity. To what extent this demand is met by green secondary energy carriers is a result of the optimization.

Based on the arguments laid out in section 3.3.1, the solidEU transformation pathway builds on the hydrogen based MeOH production route. Process substitution consequently commences in 2025. In absence of data concerning the age structure of current MeOH steam reforming units a linear capacity exchange rate of 4 % p.a. based on a technology lifetime of steam reforming units of 25 years is assumed. Under these assumptions 2025 poses the latest possible year for the beginning of measure implementation to avoid stranded steam reforming assets until 2050. Like the HVC and NH_3 transformation, the cost-optimal procurement of hydrogen required for MeOH synthesis is optimized in ISAaR.

For chlorine production significant changes to the incumbent process are not expected. In solidEU the remaining diaphragm cells in Germany and France are replaced until 2050. This replacement process is modeled as an efficiency improvement of the electrolysis cell. It also occurs in quEU.

The discussed emission reduction pathways for solidEU show that deep emission cuts in basic chemicals production require emission free electricity, hydrogen and/or feedstock (i.e., carbon sources). Figure 38 shows the resulting transformation pathways and changes in energy consumption for the modeled processes.

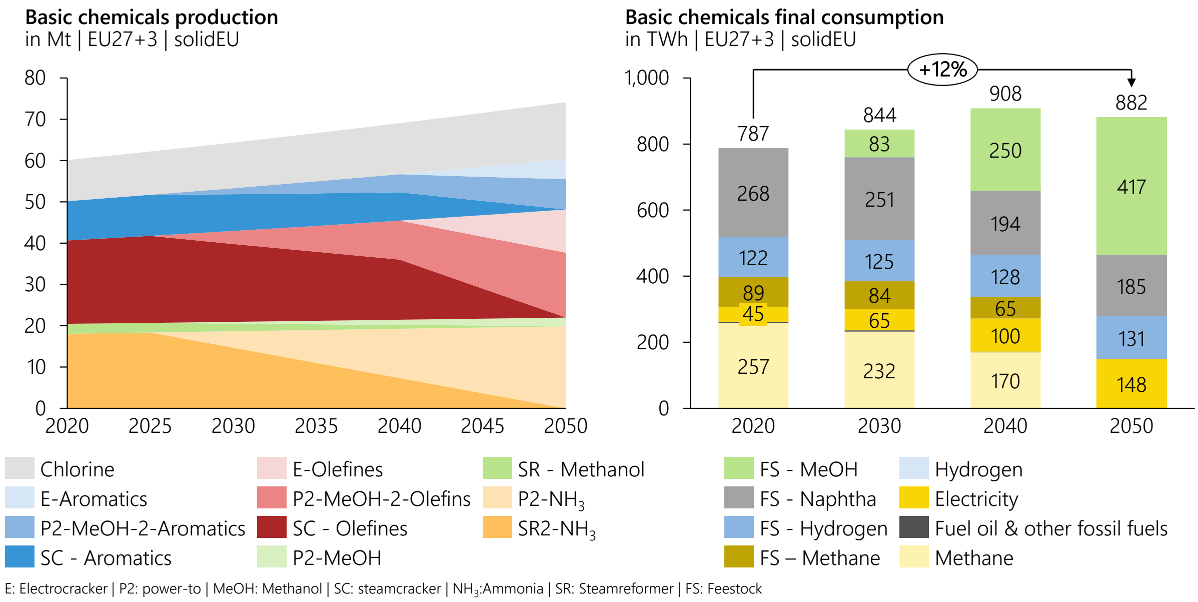


Figure 38: solidEU transformation pathway for SmInd EU basic chemicals processes[105]

The left-hand side of the figure shows the transformation of production tonnages for ammonia, HVC and methanol from 2020 to 2050. The right side shows the development of energy and feedstock final consumption as a result of economic growth and measure implementation. Total final consumption for the modeled processes in the chemical industry increases by 12 % between 2020 and 2050. This is driven by a feedstock increase of ~50 % in the same period. Electricity, fuel oil and natural gas FEC reduces significantly (52 %) through electrification of steamcrackers and steam reformers. Direct hydrogen demand increases only as a result of economic growth as ammonia and MeOH production increase until 2050 (~1 % p.a.).

By 2050 the transformation of steamcrackers to MTO/MTA processes leads to an MeOH demand of 417 TWh. This is an equivalent of ~75,500 kt_{MeOH}, which is approximately 30 times the current MeOH production volume in the EU27+3. The implementation of E-HVC as of 2040 causes an increase in electricity

[105] Energy carriers <0.1 % of FEC suppressed for visualization purposes.

consumption while displacing further natural gas demand used for heat provision in conventional steamcrackers. 185 TWh of naphtha feedstock remain in 2050, as electrocrackers require long chain hydrocarbons as feedstock. To achieve deep emission cuts not only energy, but also the feedstocks methane, naphtha and hydrogen need to be climate neutral. In a static calculation the procurement of these feedstocks can lead to an additional 1600 TWh_{el} of electricity if hydrogen is produced via electrolysis, MeOH via P2MeOH and green naphtha via Fischer-Tropsch synthesis.[106] This equates to ~50 % of current total EU27+3 electricity demand for industry, transport, and buildings.

In summary, the transition of the basic chemicals modeled bottom-up in SmInd EU builds on hydrogen or hydrogen derivatives. Hereby, the production of green chemical feedstock can pose a significant additional driver for electricity demand, if produced in the EU and via green hydrogen (based) production routes of climate neutral energy carriers. For the purpose of this thesis it is assumed that green naphtha and MeOH are imported.

Non-Metallic Minerals – Cement, Lime, Container Glass and Flat Glass

The solidEU transformation pathway for the modeled non-metallic minerals processes is based on [5, 37, 60, 62, 63, 92–95]. The age structure of the modeled processes in Europe could not be considered in this thesis, due to a lack of literature values.

For the cement and lime production processes a combination of biomass, RES waste and H_2 fuel substitution as well as CC constitutes the solidEU transformation pathway. Fuel substitution measures are based on the phase-in of multi-fuel burners for solid and liquid energy carriers as well as H_2 burners, which substitute natural gas burners in the long-run. Considering, that additional CAPEX from burner substitution measures are low compared to total costs [86], it is assumed that rolling substitutions for multi-fuel burners occur between 2021 and 2050. Hydrogen burners are installed as of 2040. Despite the progressive character of solidEU, the fuel switch from fossil solid fuels to biomass and natural gas to hydrogen commence 2030 and 2040 respectively. Both fuel switch measures are completed by 2050. The relatively late starting periods for fuel switch measures are a result of the limited sustainable biomass potential and the effort to avoid a hydrogen FEC peak around 2030. Hereby, it is important to note that in the solidEU scenario biomass is shifted from the transport and household to the industry sector. Through the continuous transformation of these sectors biomass becomes available for use in the industry.[107] In addition to fuel switch measures for both lime and cement production, post-combustion CCS is considered as a deep emission reduction measure as of 2025. This includes the underlying assumption that the construction of a CC infrastructure including respective storage solutions commences simultaneously. This results in BECCS, which leads to negative emissions by capturing biomass and RES waste-based combustion exhaust gasses in cement and lime production.

SmInd EU considers that a reduction of primary steel production (e.g., through the implementation of greenhouse gas abatement measures) and a phase out of lignite fired power plants leads to a reduced availability of blast furnace slag. This in turn results in an additional demand for clinker to sustain the level of cement production, causing the energy demand per ton of cement to rise. Hereby, the substitution ratio between clinker and slag is 1:1 [142]. Furthermore, the phase-out of primary steel production leads to a reduction of lime demand, which is an important additive for building slag. This is considered through the definition of consistent exogenous production tonnage developments for lime and primary steel production [52].

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[106] For this calculation MeOH production initially causes 155 TWh of electricity, 475 TWh of hydrogen and 104 Mt_{CO2} of CO_2 demand for MeOH synthesis. Electrolysis and direct air capture are assumed for providing the hydrogen and CO_2, respectively. Electrolysis efficiency 66 %, DAC parameters taken from [6] and synthetic naphtha production parameters taken from [53].
[107] Confer [16] for FEC development in other sectors.

For flat and container glass, the full direct electrification via electrical container and flat glass furnaces is assumed. In solidEU electrification commences 2025 with exchange rate of 4 %/a for container glass and 7 %/a for flat glass.

The transformation pathway for solidEU is shown in Figure 39. The left-hand side of the figure shows the transformation of production tonnages for cement, lime, flat and container glass 2020 to 2050. The right side shows the development of FEC because of economic growth and measure implementation.

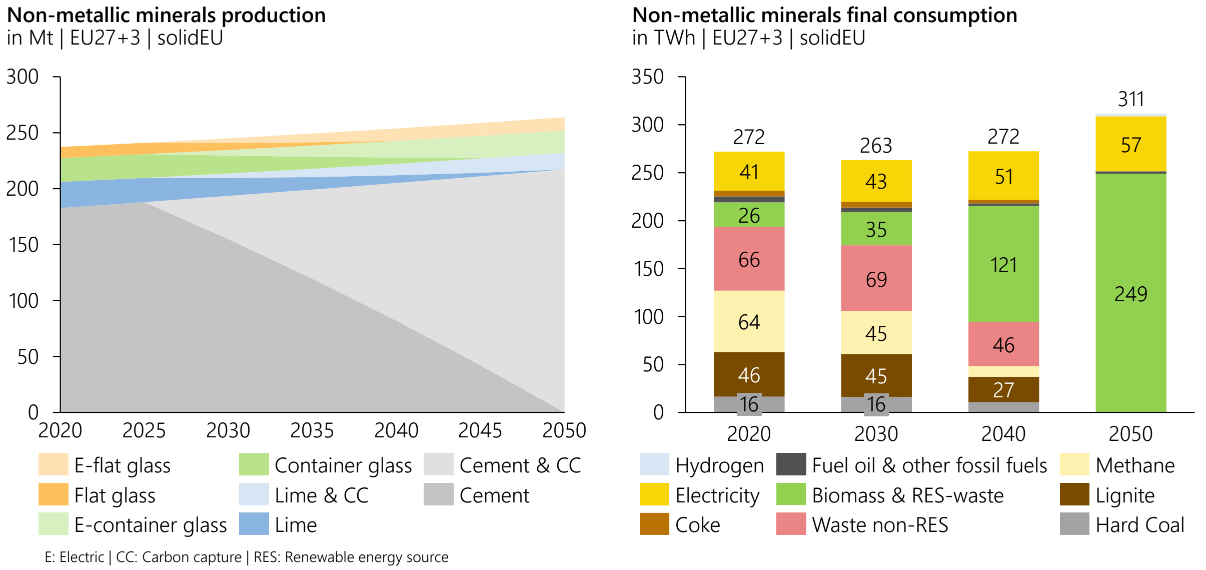

Figure 39: solidEU transformation pathway for SmInd EU non-metallic minerals processes

Total final consumption for the modeled processes in the non-metallic minerals industry increases by 14 % between 2020 and 2050. This is driven by economic growth in the cement, lime and glass production, the additional energy demand for CC measures and the increase of the clinker-cement factor to 1 by 2050. The latter is a result of declining slag availability from primary steel production and leads to an additional 50 TWh of fuel demand in 2050. As shown in in Figure 39, the phase-out of primary steel production until 2050 also leads to a strong decline in lime demand and production in Europe. Nevertheless, the transformation of the lime and cement processes is dominated by the 10-fold increase of biomass and RES waste fuel usage between 2020 and 2050. This equates to 223 TWh or ~73 % of total biomass demand in the industry sector in 2017. This bio-fuel demand increase does not exceed the additionally available sustainable biomass potential for the industry in solidEU 2050. Excluding an intersectoral shift of biomass the authors of [52] assume an increase in sustainable biomass potential for the EU industry of 250 TWh until 2050. In solidEU this number is increased by the intersectoral shift of biomass from the household, tertiary, and transport sectors to the industry sector by ~300 TWh.[108] This results in a total available sustainable biomass potential for the EU27+3 industry sector of ~860 TWh by 2050. Furthermore, it should be noted that the combination of biomass usage and CCS enables negative emissions. While the growth in biomass demand is predominantly driven by fuel substitution, in 2050, approximately 40 TWh of biomass and RES waste result solely from additional CC fuel demand. CC also leads to ~10 TWh of additional electricity demand in 2050. This is higher than the increase resulting from the electrification of flat and container glass.

In summary, the transition of the non-metallic minerals processes modeled bottom-up in SmInd EU builds on BECCS. Hereby, the sustainable biomass potential in the EU27+3 is not exceeded. A comparably low increase in electricity demand results from CCS and the electrification of glass production.

[108] 40 TWh are shifted to the energy supply-side.

Other Processes and Cross-Sectional Measures

The solidEU transformation pathway for aluminum, paper, pulp and print, dairy production and the share of the industry not covered by concrete technological measures is based on [1, 5, 6, 37, 85, 98, 143]. The age structure of these processes and applications for Europe is unknown.

In Aluminum production a combination of innovative electrodes and a slight shift from primary to secondary aluminum is assumed. The latter is not included in the measure list since it is reflected in the exogenous production tonnage development. Conventional primary aluminum cells are replaced with innovative electrodes starting in 2035. This poses the earliest year of implementation in which both inert anodes and wetted cathodes reach market readiness. Due to the comparably low lifetime of aluminum electrolysis cells the transformation is completed by 2045.

For paper, pulp and print as well as dairy production the direct electrification of drying and heating processes is assumed. Under the favorable technology development circumstances in solidEU, the required technologies - high temperature heat pumps and electrode boilers – will be market ready by 2025. For low-temperature electrification <100 °C an industrial ground source heat pump is deployed. For the medium-temperature band 100 °C – 500 °C a combination of heat pump and electrode boiler is assumed. As described in section 3.3, low- and medium-temperature electrification is modeled as a cross-sectional measure. These technologies are therefore parametrized independently. Measure implementation is completed by 2045, assuming a technical lifetime of incumbent heating technologies of 20 years.

To allow for deep emission reduction in solidEU, further CSMs are required, since not the entire industrial technology structure is uncovered in this dissertation. Hence, multi-fuel and hydrogen burners are assumed for process-heat >500 °C as well as steam provision in the chemical industry. Hence, all process heat applications not modeled by bottom-up processes are addressed by fuel switch CSM. While competing interdependencies with proxy efficiency measures in these application areas exist, efficiency improvements lead to the reduction in substitutable FEC through fuel switch CSM. This in turn leads to a reduction of the demand for scarce emission-free fuels. Consequently, both measures are deployed simultaneously.

5.4 Preliminary Summary

In the previous sections an integrated scenario process was developed and applied to answer the question of how qualitative context scenarios can be translated into a quantitative framework to derive a consistent socio-technical European deep emission reduction scenario for the industry sector.

Based on a review of existing integrated scenario literature a demand for additional steps enabling the structured quantification of context scenarios was identified. The latter was filled by developing the so-called *From Word to Value* procedure. At the core of this procedure lies the descriptor-parameter-matrix, which facilitates the matching between context scenario descriptors and model-exogenous parameters. By identifying direct, weak, and unconnected parameter-descriptor pairs, a basis for the traceable quantification of context descriptors is created. The matching procedure also supports the identification of critical descriptors which are not addressed by parameters within the model landscape. This could indicate a demand for further iterations aimed at redefining descriptors or adding parameters to establish the missing links. Ultimately, the *From Word to Value* procedure poses a structured approach for linking context and quantitative scenarios and thereby facilitates the linkage between sociopolitical and technoeconomic arguments.

The developed integrated scenario process was then applied to derive two scenarios: quEU and solidEU, whereby quEU is a scenario in which climate targets are not achieved, and solidEU poses a deep emission reduction scenario. Since quEU and solidEU are holistic energy system transformation storylines, the degree of detail in the industry sector was insufficient to connect all relevant abatement measure implementation parameters to respective descriptors. Consequently, the scenario quantification procedure was augmented by additional research, delivering the necessary level of detail for quantifying industry branch specific transformation pathways in the spirit of the quEU and solidEU scenarios.

6 Balancing of Emissions and Costs

In this section the method and core assumptions for emission balancing (section 6.1) and the cost approach (section 6.2) are described. Furthermore, the advantages and disadvantages of using CO_2 abatement costs as a cost evaluation metric as well as solutions aimed at eliminating these disadvantages are discussed in section 6.2.1.

6.1 Emission Balancing

In this dissertation emission balancing is confined to scope 1 and scope 2 CO_2 emissions [144], whereby scope 1 emissions result from the combustion of fuels for energy supply in industrial applications, and scope 2 emissions are indirect emissions associated with the production of secondary energy carriers such as electricity or hydrogen. Upstream or downstream emissions along the value chain of industrial goods and production processes (scope 3) are not taken into account.

Scope 1 and 2 energy related emissions in the industry sector are derived by scaling FEC with CO_2 emission factors. The latter are country, energy carrier and time specific. In addition to energy related emissions, industrial process related CO_2 emissions are included. As described in section 3.2 the latter are process dependent. Where scope 2 emissions are depicted, the indirect emissions from secondary energy carrier consumption (e.g., electricity, hydrogen) are allocated to the industry sector. As described in sections 2 and 5.2.3, emission factors for hydrogen, electricity, synthetic fuels, and synthetic methane are calculated based on ISAaR model simulation results. For the evaluation of industrial CO_2 abatement measures and transformation pathways in section 7, average annual country specific emission factors are calculated. Thereby the hourly (for electricity and hydrogen), daily (for synthetic methane) and annual (for synthetic fuel) primary energy input required to generate secondary energy carriers as well as the technical specifications (e.g. efficiency) of the respective production units (e.g. electrolyzers, powerplants) are evaluated.[109] These emission factors therefore reflect the changes on the energy supply-side induced by the quEU and solidEU demand-side transformation pathways.[110] Since emission factors are partially scenario-dependent, an overview of the respective values is provided in section 5.

6.2 Cost Evaluation Approach

Calculating the costs resulting from an investment decision is linked to the concept of opportunity cost Decisions for or against investing are always made under consideration of alternatives [145]. The alternative to investing can also be not to invest at all. An investment case is therefore always impacted by the choice of the reference case. This in turn means that cost evaluation results must be interpreted in the context of the selected reference and that the explanatory power of such evaluations is limited to the decision situation.

These fundamental aspects of investment decision making also apply to the complex field of long-term industrial transformation scenarios. Thereby, the complexity results from the high degree of technoeconomic understanding required to purposefully select, parametrize, and evaluate both the reference and alternative technologies and systems, while simultaneously dealing with uncertain future developments. Despite the complexity of the decision situation, it is also crucial that non-scientific stakeholder groups such as policymakers or practitioners understand such cost evaluations. Consequently,

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[109] Confer [13, 137] for further details concerning the exact calculation method.

[110] As described in section 2, quEU and solidEU are holistic energy system scenarios including demand development data for all energy end-use sectors. The resulting supply-side transformation is therefore not solely a reaction to the industrial transformation. The quEU and solidEU demand-side transformation pathways for households, tertiary and transport sector are available in [16]. Supply-side results are available in the interactive ISAaR dashboard [140].

a strong demand for key figures and visualizations exists, aiming at reducing the complexity of the decision situation to facilitate the communication of key messages.

With respect to the evaluation of the costs of abatement measures and pathways, ACs and their visualization in so-called marginal abatement cost curves (MACC) are a frequent method of choice. Despite their broad acceptance and utilization amongst academic and political stakeholders, ACs are however frequently published without the necessary guidelines and information which are required to mitigate the possibility of misinterpretation. In the following sections, the concept of ACs and MACCs is therefore explained, and an analysis of the main advantages and disadvantages of ACs as well as measures to counteract these disadvantages are suggested (cf. section 6.2.1).

Cost Methodology

ACs handle complexity by reducing the decision situation to one key figure, which expresses the additional or avoided costs for mitigating one unit of CO_2 (€$_{2017}$/tCO_2). Expression (6-1) shows that ACs are calculated as the cost difference between an abatement measure and reference technology divided by the emission difference between the abatement measure and reference. Thereby the expression is only valid for positive emission differences.

$$ac_{r,b,p,m,ref,t} = \frac{\Delta c_{r,b,p,m,ref,t}}{\Delta em_{r,m,ref,t}} = \frac{c_{r,b,p,m,t} - c_{r,b,p,ref,t}}{em_{r,ref,t} - em_{r,m,t}}$$
$$= \frac{\left(a_{r,b,p,m,opex,t} - a_{r,b,p,ref,opex,t}\right) + \left(a_{r,m,capex,t} - a_{r,ref,capex,t}\right)}{\left(eem_{r,m,t} + pem_{r,b,p,t}\right) - \left(eem_{r,b,p,t} + pem_{r,b,p,t}\right)} \quad (6\text{-}1)$$
$$with\ \Delta em_{r,m,ref,t} > 0$$

$$a_{r,m,opex,t} = opex_{r,m,t} \text{ and } a_{r,m,capex,t} = I_{r,m,t} * \frac{i*(1+i)^t}{(1+i)^t - 1} \quad (6\text{-}2)$$

ac: abatement cost	Δc: cost delta	Δem emission delta	a: annualized cost
eem: energy-related emissions	pem: process emissions	r: region	m: abatement measure
ref: reference	t: time	b: industry branch	p: process
$capex$: capital expenditure	$opex$: Operating expenditure	I: investment	i: discount rate

To calculate the cost difference between two measures, the total costs of the abatement measure are subtracted from the total costs of the reference. Total costs, $c_{r,b,p,m/ref,t}$, consist of CAPEX and OPEX. OPEX is treated as real additional or avoided annual costs of measure implementation. CAPEX is annualized using the right-hand side of expression (6-2). By annualizing CAPEX, investments are distributed evenly over the depreciation period of the respective technology and under consideration of a discount rate.[111] AC is therefore calculated as annualized additional or avoided cost of measure implementation.

In this dissertation ACs are calculated for individual abatement measures as well as the quEU and solidEU transformation pathways. To calculate the latter, the costs and avoided emissions of all measures implemented along the transformation pathway are aggregated. Consequently, costs and ACs of transformation pathways are expressed as additional or avoided costs with respect to the incumbent reference technology.[112] Furthermore, ACs can be evaluated for a given year or as cumulative over a certain time. Hereby cumulative ACs consider cost and emission developments, thereby capturing future information and assumptions about the energy system and industry sector.

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[111] In this dissertation the depreciation period is set to the technology lifetime or investment cycle of a technology. CAPEX includes fixed operating costs, since these costs are predictable and can be considered during the investment decision.

[112] Expressing costs as cost differences with respect to a reference is also necessary since balancing total EU27+3 industrial investments is not possible due to a lack of data. This would require detailed knowledge about the costs of all incumbent technologies and investment cycles. To the best of the author's knowledge, databases providing such information do not exist.

Both annual and cumulative transformation pathway costs for quEU and solidEU are disclosed as additional or avoided cost with respect to the status quo technology (i.e., year 2020), but refrain from visualizing and interpreting the cost difference between the quEU and solidEU scenarios. In this sense, the scenario evaluation in this dissertation differs from classical European [100, 146] and German [81–83] political energy studies. In these studies, mostly a conservative scenario in which climate targets are not achieved is constructed and then compared to a deep emission reduction scenario. Cost evaluations of deep emission reduction scenarios are then often performed with respect to these reference scenarios (e.g. [82]). The initial situation is therefore comparable to this dissertation, since the quEU scenario portrays a transformation pathway which is comparable to that of a typical so-called reference, business-as-usual or trend scenario.[113] solidEU in turn is a deep emission reduction scenario. The integrated scenario process performed in this dissertation however shows that the socio-political environment and therefore the *scenario worlds* of these scenario types differ significantly.[114] This raises the question of the extent to which cost comparisons between fundamentally different scenarios are meaningful.

A variety of additional aspects enhance the doubts concerning the explanatory power of cost-difference calculations between reference and deep emission reduction scenarios:

- The use of reference scenarios as a basis for calculating cost differences disguises the true CAPEX and OPEX costs of deep emission reduction scenarios. Reference scenarios do not internalize the cost of negative externalities which would result from failing to achieve climate targets. By calculating the costs of climate protection with respect to reference scenarios, additional costs are therefore overestimated. On the other hand, using reference scenarios as a point of comparison can also lead to additional costs being underestimated. By taking a reference scenario in which some, but insufficient investment into climate protection technologies is performed, additional costs of climate protection are reduced. This is especially the case if the reference scenario itself is ambitious (e.g. [8]). From an academic point of view, underestimating the costs of deep emission reduction is equally harmful to overestimating these costs.
- Considering the complexity of scenarios and the variety of underlying assumptions it is questionable to what extent the differences between scenarios can be taken into account in the cost evaluation. While this might be possible with respect to quantitative parameters, the interpretation of the socio-political context is difficult.
- Investment decisions are decision situations in which alternatives (including the option not to invest) are evaluated. This is reflected by the AC calculation where CO_2 abatement measures are compared to a reference technology. The reference itself is however also affected by the configuration of the respective scenario world. For a meaningful evaluation of abatement measures the point of comparison should therefore be part of the same scenario setting.

Taking these aspects into consideration, it should be the aim to define a reference point for cost evaluations which itself is easy to interpret and minimizes the possibility for misinterpretation. A plausible point for comparison is the status quo or a simple economic-growth scenario. The scenario evaluation and especially the cost calculations in this dissertation are therefore performed with respect to the energy system in 2020. The costs and emission evaluation of an economic-growth-baseline are provided as additional information which shows what would happen if no climate action took place.

[113] In a highly dynamic environment such as the European energy transition, the meaning of terms such as *reference*, *business as usual* or *trend* are in constant transition and therefore misleading. By connecting scenario developments to a scenario world using distinct scenario headings, such as quEU and solidEU, this can be avoided. These scenario titles are also a constant reminder for the reader, that two entirely different future pathways are being compared and that the interpretability of differences is restricted.

[114] While the mentioned studies do not apply an integrated scenario process, it is likely that the socio-political differences between reference and climate protection scenarios are comparably drastic.

Cost Perspective

In addition to the defined measure and reference technology, the quantification and meaning of ACs depends on the cost perspective. The cost perspective influences the cost components included in the total cost calculation as well as the discount rate [37]. In this dissertation ACs are evaluated from the investor and system perspective as defined in [6]. Table 15 summarizes the differences between CAPEX and OPEX calculations depending on the cost perspective.

The investor perspective includes all cost components visible to an industrial actor who faces the decision of measure implementation. The relevant OPEX parameters are energy carrier prices including all taxes, levies and surcharges, emission certificate prices and other O&M costs. In this dissertation it is assumed that these components remain constant over time. The underlying idea is that while the purpose of taxes, levies and surcharges on energy prices might change over time, their role as a financing mechanism for certain system components will also be necessary in the future. CAPEX is affected indirectly, since the investor sees a discount rate which reflects the investor's opportunity cost. In most cases the latter is defined by profit expectations of the respective company [141, 147].

Table 15: Overview of cost components for CAPEX and OPEX calculation by cost perspective[115]

Component	System perspective	Investor perspective
CAPEX	- Annualized with societal discount rate	- -Annualized CAPEX with investor discount rate
OPEX	- Energy carrier and feedstock prices differentiated by country - O&M cost	- Energy carrier and feedstock prices differentiated by country an industry branch including taxes, levies and surcharges - EU ETS certificate prices - O&M cost

As opposed to the investor perspective, the system perspective does not include actor-specific price elements such as taxes, levies and surcharges and emission certificate prices. Hence, any price components which solely re-distribute costs are excluded. The system perspective can be interpreted as a simplified approach to assuming a macroeconomic cost perspective. This results from the fact that only new actual costs to the system are balanced, but typical macroeconomic cost elements such as externalities and transaction costs are not considered. Furthermore, the assumed so-called societal discount rate does not reflect short-term profit expectations of industrial actors, but a more long-term and welfare-oriented investment perspective [2].

Comparisons between the actor and investor cost perspective enable analysis concerning the effect of taxes, levies and surcharges, emission certificate prices as well as investor opportunity costs on the implementation of abatement measures. These cost components are subject to decision making by the regulator or industrial actors and are therefore potentially adaptable. Thus, discrepancies between AC from the system and investor perspective can indicate room for policy making.

Cost Calculation by Measure Cluster

The cost and emission calculations required to derive ACs vary depending on the measure implementation cluster in SmInd EU. A summary of the most important aspects and assumptions is provided below. It is based on the Master's thesis [137], which was supervised by the author of this dissertation.

For efficiency measures, costs consist of specific CAPEX and avoided OPEX due to measure implementation. Thereby the assumed reference case is that no investment occurs. For process efficiency measures specific CAPEX refers to the investment per ton of product. For CST efficiency measures, CAPEX is specific to the

[115] As described in section 5.2.3 some energy carrier prices (e.g. hydrogen) are actually energy carrier costs, since they are based on a bottom-up cost calculation.

measure implementation cost for an average company.[116] For proxy efficiency measures specific CAPEX are derived using the same logic as for specific energy savings. Hence, the proxy measure CAPEX is based on the specific CAPEX of the quantified technological efficiency measures. OPEX results from energy carrier cost savings and if applicable, lower costs for EU ETS certificates.

For process substitution measures, ACs are calculated as the difference between the innovative process route and the respective reference process route (e.g., secondary vs. primary steel production). Specific CAPEX expresses the cost of investing in the process per ton of production capacity. OPEX is derived via the energy carrier specific final consumption of processes and the according energy carrier prices as well as O&M costs. Both energy and feedstock costs are considered. For the investor perspective process as well as energy related emissions determine the demand for emission certificates for energy intensive processes.

For direct electrification of low- and medium-temperature heat measures the cost differences are derived by calculating the costs for heat procurement via a fossil reference technology and the defined electrical alternative. Hereby specific CAPEX is defined for an average EU company. OPEX differences result from the respective difference in energy carrier and emission certificate costs. Despite the implementation of direct electrification measures as cross-sectional measures, industry branch specific costs are calculated. This is possible since the displaced fossil and additional electrical FEC is calculated country, industry branch, energy carrier, and application specific. Industry branch specific CAPEX values are not considered, which is a possibility for further research. However, the analysis in [6] shows that average CAPEX shares for the reference and electrical technology in low- and medium temperature heat electrification are ~5 % and ~15 %, respectively. With respect to the aim of this dissertation, which is to calculate the scenario-based costs of the European industrial energy transition, the influence of these costs on total ACs is considered acceptable.

For other fuel switch measures, ACs are calculated solely based on OPEX (cf. section 3.3.3). Like the other measure clusters, OPEX results from differences in energy carrier and feedstock costs as well as emission certificate prices. The selected reference for these measures is the status quo of energy carrier consumption before measure implementation.

Ultimately ACs for carbon capture measures are based on specific CAPEX per ton of captured CO_2 as well as differences in OPEX. Through CC, additional energy is consumed, leading to an energy carrier and emissions certificate cost increase. However, both process and energy related emissions are abated through CC measures, resulting in cost reductions. The reference assumed for carbon capture measures is that CC is not im plemented.

Marginal Abatement Cost Curves

MACCs are a visualization tool used to facilitate the comparison of individual CO_2 abatement measures regarding ACs and avoided emissions. Figure 40 shows an exemplary MACC including explanations for its core components. The result of expression (6-1) builds the ordinate, the denominator the abscissae.

MACCs started receiving increasing attention since the global McKinsey MACC was published in the McKinsey Quarterly Review in 2007 [148]. Since then, a variety of MACCs have been published for different years and regions such as the recent examples in [2, 82]. MACCs are a popular policy advice tool, mainly due to their clarity and at the same time high density of information. It is however precisely because of the compact presentation of complex decision situations, that there is a risk for misinterpretation. Hence, when using MACCs and ACs in general, a clear picture of their advantages and limitations is necessary to mitigate the risk of misinterpretation.

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[116] Similar to specific energy savings for CST measures, total costs of measure implementation are calculated and subsequently divided by the number of companies per industry branch in each country.

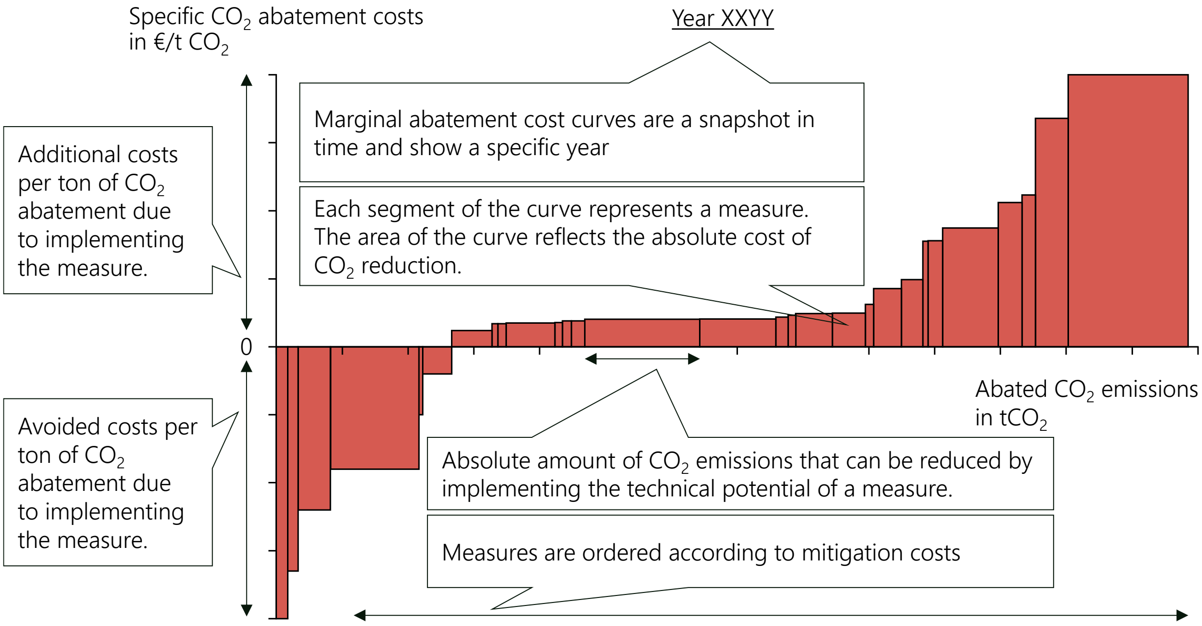

Figure 40: Exemplary MACC including explanations

The following section provides solutions aimed at improving the concept of conventional ACs.

6.2.1 Improving CO_2 Abatement Costs

Since MACCs are a visualization tool, the advantages and disadvantages of the concept of ACs also apply to them. In the past, the assessment of advantages and disadvantages was directed mainly at MACCs, rather than the concept of ACs in general [141]. This results from the fact that MACCs visualize ACs and therefore pronounce both the strengths and weaknesses of the concept. Advantages and disadvantages described below address the concept of ACs and therefore also apply to MACCs.

The advantages of ACs and their presentation in MACCs mainly relate to the concise and easy-to-read presentation of costs and potentials of abatement measures. Since costs are expressed in specific CO_2 savings, the intersectoral ranking of abatement measures is possible. Plotting ACs in MACCs also provides the possibility of an ad-hoc indication of the effect that a certain CO_2 price can have on the implementation of abatement measures. Furthermore, it provides a starting point for measure comparison. Hence, MACCs can be used as a tool for quick and comprehensive policy advice and can build the basis for the design of climate policy instruments.

To avoid misinterpretation of ACs, they should however be viewed in the light of their shortcomings. As described in detail by [141] and later by [6, 86, 149] and also in this dissertation, it is precisely because of the reduction of complexity that a risk for misinterpretation exists. However, this risk can be reduced by considering a variety of methodological extensions to the concept of ACs. Table 16 lists the main limitations of ACs including suggestions on how to counteract these disadvantages.

The limitations of conventional ACs are summarized in three categories: data transparency, methodological approach, and macroeconomic and qualitative criteria. In the following sections these drawbacks are explained, and methods to reduce them are described.

Table 16: Limitations of CO_2 abatement costs and methods to counteract them

Limitations of abatement costs [141]	Methods to reduce limitations in this dissertation
Data transparency	
Lack of transparency of assumptions	Data appendix and explanation of assumptions in scenario process
Possibility of inconsistent baseline emissions	Use of a consistent data and modeling framework
Measure interdependencies neglected	Measure identification and selection method (cf. section 3.3.2)
Simplified technology cost structure	Supplementary matrix visualization
Suggest an implementation order	
Uncertainty & sensitivities not considered	One-factor-at-a-time sensitivity analysis, Monte Carlo simulations, Morris Screening and matrix visualization
Methodological approach	
Limited to one point in time and space	Transformation pathway analysis using a model- and scenario-based approach
No representation of path dependencies	
No representation of system effects	
Macroeconomic and qualitative criteria	
Ancillary benefits & limitations neglected	Multi-criteria evaluation scheme for qualitative criteria

6.2.2 Data Transparency

A possibility for misinterpretation of ACs exists if data and assumptions required to validate the cost calculation are not disclosed. Despite being a known disadvantage such disclosure is still not the case in influential reports such as [2, 5, 82, 148]. This dissertation takes the position that the data required to evaluate both cost and emission differences should be disclosed to a degree which allows rudimentary data validation, and the assumptions and method used to model abatement measures are therefore described in detail.

A further risk of misinterpretation exists if measures are not calculated based on consistent baseline emissions and if measure interdependencies are not considered. Consistent baseline emissions are necessary to provide a level playing field for abatement potential calculation. Therefore, each measure should be evaluated using a consistent set of FEC and emission factor data. In this dissertation, this is achieved since all calculations are based on the energy carrier application balances (cf. section 3.1). Furthermore, emission factors for primary energy carriers are derived from the same set of literature for all models in the model landscape. The emission factors for secondary energy carriers are model results and use the primary energy carrier emission factors as input. Hence, measure evaluation is performed based on a consistent data set. Furthermore, the integrated scenario process ensures that measures are evaluated within a consistent scenario world. In addition, measure interdependencies are considered during the measure selection process (cf. section 3.3.2). This eliminates the risk of overestimating abatement potentials if the sum of all measures is calculated during measure evaluation.

In addition to the lack of data transparency, ACs and their representation in MACCs strongly aggregate reference- and measure-related data. Hence, the cost structure and therefore the drivers of ACs as well as possible data sensitivities remain hidden. Furthermore, the ranking of measures visualized in MACCs suggests a recommended order of implementation. Both aspects disguise the fact that AC calculations are based on a variety of uncertain assumptions and that they are typically not the only criterion for the actual implementation of abatement measures in practice.[117] The analyses performed in [6, 86, 149] show that the

[117] Criteria such as the amortization period or internal rate of return are more important to practitioners.

explanatory power of ACs and MACCs can be improved by adding a so-called matrix visualization to the conventional visualization. The matrix visualization increases the transparency of the underlying cost and emission data and refrains from ranking measures. For explanatory purposes, an exemplary matrix evaluation is depicted in Figure 41.

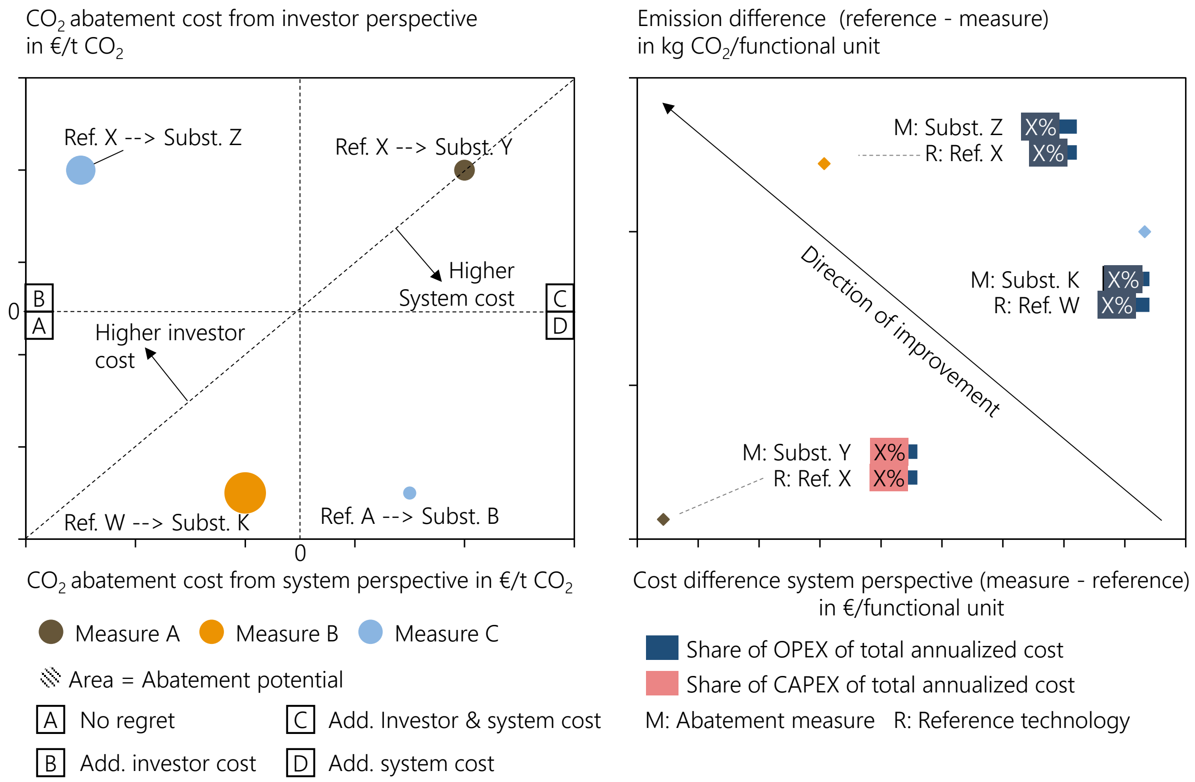

Figure 41: Exemplary matrix visualization for supplementing conventional MACCs

On the left-hand side, abatement measures are plotted with respect to ACs from the system and investor perspectives. The abatement potential is provided by the area of each bubble. The right-hand side shows the same measures, but with respect to the emission and cost difference which causes the respective abatement cost result. Thereby functional units used in the dissertation are production tonnages and the number of businesses. In addition, each measure is provided with additional information concerning the share of CAPEX and OPEX of total measure cost.

Visualizing ACs with the abatement cost matrix (ACM) yields three main advantages:

- The quadrants marked A, B, C and D in the ACM allow the comparison of investor and system perspective, whereby measures in quadrant A exhibit negative costs from system and investor perspective. These measures can be considered no regret measures. In quadrant B additional costs for investors are invoked. This results from taxes, levies, and surcharges on energy carrier prices and/or company opportunity cost. Since system costs are negative in this quadrant, measure implementation is recommendable from the system AC perspective. This discrepancy between system and investor perspective can indicate anchor points for policy measures, since the cost differences result from aspects which can be influenced. Quadrant C indicates additional costs from both perspectives. Measures in this quadrant require further R&D and implementation experience to drive down costs. Quadrant D includes measures which are favorable from the investor but not the system perspective. If the investor cost perspective includes financing incentives for measures, this can indicate that unnecessary implementation incentives exist. In this dissertation, the explanatory power of quadrant D is restricted. Measures in this quadrant lead to avoided investor costs due to taxes, levies and surcharges on energy carrier prices.

- By disclosing emission and cost differences in the ACM, further details about the reasons for the AC level of a measure are provided. This is especially important for measures with negative ACs. In a traditional MACC, measures with negative ACs are positioned on the left-hand side of the curve, thereby indicating high avoided costs. The further left a measure is positioned, the higher the perceived avoided cost. However, high negative ACs are not necessarily caused by higher cost differences between reference and abatement measure. Very low specific emission differences can also lead to strongly negative ACs. This is misleading for two reasons: firstly, the measure might not lead to high avoided costs and might not be as economical as expected due to its position in the MACC. Secondly, low specific emission differences are less favorable compared to high-specific emission differences. Hence, the correct interpretation of measures with negative ACs requires further information about the numerator and denominator of the abatement cost equation. For ACs which are visualized using classical MACCs, the visualization should therefore be supplemented by an ACM.[118]
- The cost structure of the individual measures is represented by the share of fixed and variable costs of total costs in the ACM. This also indicates sensitivities of the displayed measures and indicates whether ACs are more CAPEX or OPEX sensitive.

Despite the clarifications added to the MACC by supplementing it with the ACM, data uncertainties and sensitives are still not considered extensively. To do so, supplementary uncertainty and sensitivity analyses are required. This has been showcased in [150] which was co-authored by the author of this dissertation. In this publication the quantified process efficiency measures for the chemical industry are analyzed in further detail, by performing uncertainty and sensitivity analyses for Germany. Uncertainties are analyzed using Monte Carlo simulations to derive the standard deviations of the energy saving potentials and cost results. In addition, Morris screening and linear regression are implemented to identify which parameters influence costs and energy savings potential the most. The analysis shows that uncertainties can have a strong impact on both cost and energy savings potential of abatement measures. The complexity of the analysis however stands in contrast to the concept of ACs, which is to reduce complexity and simplify the evaluation of abatement measures for different stakeholder groups. Having demonstrated the effect of uncertainty and sensitivity analysis in [150] the topic is restricted to one exemplary one-factor-at-a-time sensitivity analysis in section 7.2.

The previous analysis of drawbacks of ACs and their representation in MACCs shows that a variety of smaller improvements exist, which can significantly mitigate the risk for misinterpretation resulting from the lack of data transparency. The solutions proposed in this dissertation focus on clarifying assumptions and data used to calculate ACs. In addition, sensitivity analysis improves the understanding of ACs of individual measures.

6.2.3 Methodological Approach

The second category of drawbacks refers to the methodological constraints of conventional ACs. The three main critique points from a methodological point of view are that ACs are static with respect to time and space, do not capture path dependencies of individual abatement measures and do not consider the effects that measure implementation has on the energy system [6, 141]. Classical ACs are therefore also described as *static ACs*. In this thesis all three disadvantages are addressed by following an integrated modeling and scenario analysis approach to evaluate the effect of greenhouse gas abatement measures in industrial transformation pathways [6].

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[118] A measure can be securely termed as *better* (w.r.t. the criteria addressed by abatement costs) compared to another, if it is located further towards the upper-left-hand corner of the right side of the ACM in Figure 41.

By following a model and scenario-based approach, the calculation of abatement pathways is no longer constrained to individual technology assessment for a certain year and region. Thereby, spatial and temporal variations of abatement potential and costs are captured, and path dependencies considered. In static ACs this is not the case. For example: static ACs do not capture the effect of efficiency measure implementation on the potential and costs of electrification measures in each year and region. Furthermore, not all relevant parameters which influence the timing of measure implementation are considered. When and if measure implementation is purposeful, is not solely driven by costs and emissions. In practice, this decision is also strongly influenced by technology investment cycles. In extreme cases, investment cycles can force the implementation of electrification measures even in cases where emissions increase in the short term. In a static MACC, this option is not considered since measures with negative emission differences are excluded by definition. Technology lock-in effects are consequently not reflected in static ACs and MACCs. These disadvantages are however alleviated in case a model-based industrial transformation pathway is determined. In this dissertation SmInd EU follows a country-specific approach for modeling abatement measure implementation between 2020 and 2050. Thereby, the long-term effect of each measure is modeled and considered along the regional transformation pathways. Through measure implementation based on natural technology exchange rates path dependencies are also considered.

As described in section 2 linking SmInd EU with the energy system model ISAaR enables the analysis of energy system effects as a result of the industrial transformation pathway. This approach poses an advancement of the concept of static ACs which was termed dynamic ACs in [6]. As shown in [6] such an analysis can be performed on an individual measure basis as well as using measure combinations (i.e. scenarios). Dynamic ACs capture the difference in costs and emissions incurred to the energy demand- and supply-side. In this dissertation, the effect of the demand-side transformation on the energy supply-side is therefore captured via the resulting energy carrier prices and emission factors. These prices and emission factors are used to evaluate the industrial transformation pathways for quEU and solidEU. In addition, an excursus focused on the effects of a high electrification scenario on the German energy system in 2030 is included in the results section. Thereby, further aspects such as vRES expansion and transmission network utilization are taken into account.

The critique points with focus on the methodological aspects reveal the limitations of the static cost approach. While disadvantages regarding data transparency can be counteracted by providing additional information and visualizations, methodological drawbacks require a different approach to abatement cost calculations. It is therefore necessary to distinguish between the concepts of static and dynamic ACs.

Static ACs are a tool for policy and decision-making support focused on individual abatement measure evaluation. It is not in the realm of the concept to capture the complex temporal and spatial interactions between measures and sectors. Even if MACCs often include measures from different sectors this does not automatically mean that complex measure and sector interdependencies are considered. Static ACs and their visualization in MACCs and the ACMs are legitimate tools which can improve the understanding of individual abatement measures and decision situations. Elaborate conclusions about the dynamics resulting from measure implementation along a transformation pathway are however not possible based on static ACs.

Dynamic ACs on the contrary capture the system dynamics of abatement measure implementation. Through the linkage of models in iterative model simulation runs, the effects of measure implementation on the costs and emissions of the energy demand- and supply-side can be included in the evaluation. This however adds complexity to the analysis and resulting measure comparisons. While this complexity is inevitable for gaining a holistic understanding of abatement measures and pathways in a highly integrated energy system, it contradicts the initially identified demand for methods to reduce complexity to make knowledge more accessible to different stakeholder groups. Ideally each measure should be analyzed including its effect on the energy system as well as other possible sectoral interdependencies. This however is unrealistic due to high transaction costs. This in turn, justifies the use of static ACs as a tool for individual measure assessment and comparison. However, if the aim is to gain insights on transformation pathways the dynamic abatement cost approach should be selected.

6.2.4 Macroeconomic and Qualitative Criteria

The third category of drawbacks addresses the lack of macroeconomic and further qualitative criteria, which are relevant for the holistic evaluation of abatement measures and transformation pathways. Both static and dynamic ACs solely grasp technoeconomic aspects related to costs and emissions. In [149] the author of this dissertation approaches the question which criteria should be considered for the holistic evaluation of abatement measures from a multi-criteria analyses angle. The aim was to identify relevant criteria for the evaluation of industrial abatement measures through an unbiased review of MCA literature. Figure 42 shows the result of this process.

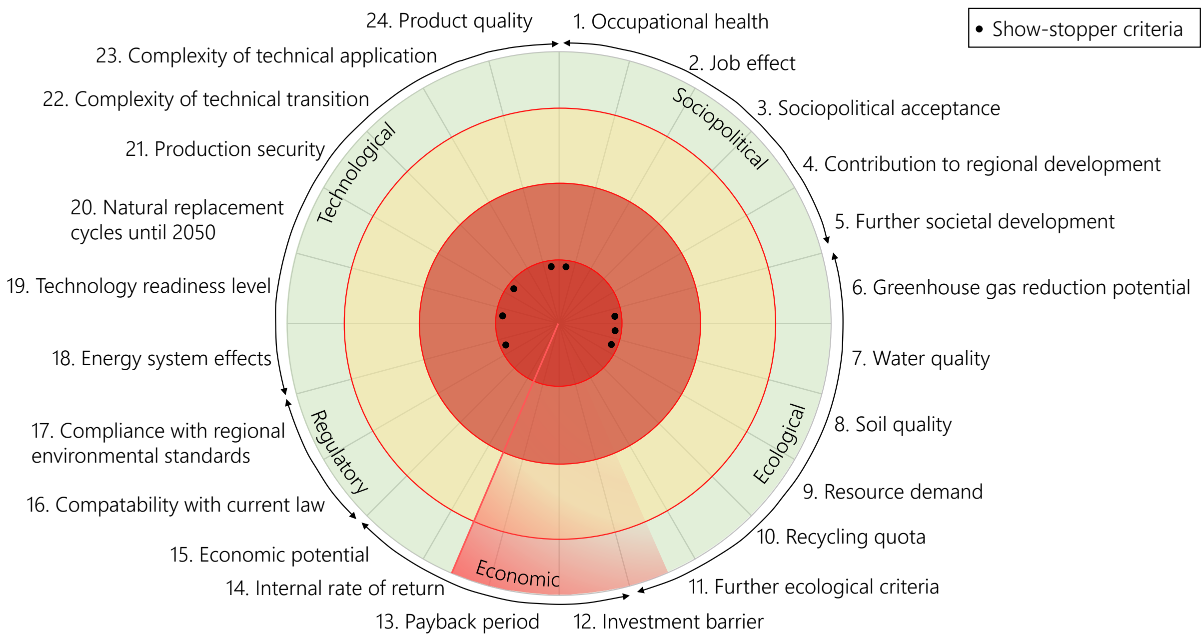

Figure 42: Radar for the holistic evaluation of emission abatement measures in the industry[119]

The method implemented to derive the 24 criteria depicted in Figure 42 is shown in Table 17. It borrows from the classical development stages of an MCA tool [152].

Table 17: Step-wise method for deriving the evaluation radar

Steps for creating a classical MCA tool	Meaning of each step for the evaluation radar
1. Context definition	Abatement measure evaluation through stakeholders
2. Definition of alternatives for evaluation	Industrial abatement measures
3. Definition of criteria and scoring methodology	24 criteria in 5 clusters
4. Normalization of scoring methodology	Traffic light system
5. Weighting of criteria	No weighting, instead definition of showstopper criteria
6. Calculation of total score and ranking of alternatives	No ranking, instead evaluation of single measures or pairs
7. Evaluation and analysis of results	Identification of implementation barriers
8. Sensitivity analysis	Not applicable since criteria are not weighted

In steps one and two, the scope of the analysis is defined. The focus in this application lies on the evaluation of industrial abatement measures through stakeholders from academia, the industry, and policymakers.

[119] See the appendix for further details on the individual criteria including main literature used to derive them. See [151] for an extensive bibliography.

Step three focuses on the identification and clustering of the evaluation criteria. The criteria in Figure 42 as well as the respective clusters are derived based on 66 publications with a thematic focus on MCA of abatement measures [151]. A selection of the relevant literature per criterion is shown in Appendix 9.5. Based on [152, 153], the following principles are considered when selecting and defining the criteria:

- High coverage of the aspects relevant to the evaluation of industrial abatement measures
- Selectivity/discriminatory power of criteria
- Measurability of criteria
- Broad relevance of criteria for all industry branches

Criteria are selected based on the frequency with which they are mentioned in the literature as well as their fit with respect to the previously mentioned principles. The listed criteria are clustered regarding their core aspects and assigned to the impact dimensions of sociopolitical, technological, ecological, economy and regulatory aspects [154]. Ultimately a scoring methodology for each criterion is developed through literature research and internal discussions. To allow for the uniform evaluation of the diverse criteria each scale (whether quantitative or qualitative) is normalized by translating it into a simple traffic-light system (step four).

In step five, the weighting of criteria was substituted through the definition of show-stopper criteria. The latter are criteria which can lead to the exclusion of abatement measures, in case of a negative evaluation. This step was adapted, since the aim of the radar is not to derive a ranking of measures, but to provide an overview of potentially relevant additional criteria. Furthermore, show-stopper criteria are of practical relevance and can supplement AC analyses, while the measure rankings in MCA are highly subjective and their usefulness in practice is questionable.

Criteria 1, 6-8, 17, 19 and 21 (cf. Figure 25) are defined as stakeholder perspective independent show-stopper criteria. Hence, despite a possibly high abatement potential and/or negative ACs, measures should be excluded from further analysis if:

- Irreversible damage to the environment or health of employees or the population is caused (6-8)
- Non-compliance with legally required environmental standards is the case (17)
- A TRL less than 9 does not allow implementation at industrial scale (19)
- The reliability of the production plant or product quality is negatively impacted (21, 24)

Compared to classical MCA analysis, steps six to eight in the table are either redefined or excluded for this analysis. Since the aim of the radar is to guide individual or pairwise measure evaluation a rank order is not calculated in step six. The evaluation in step seven focuses on the identification of implementation barriers. Step eight is excluded, since a quantitative rank order is not determined.

In the analysis of abatement measures in section 7.1, only measures which pass the show-stopper criteria are depicted. It is however not in the scope of this thesis to evaluate each measure with respect to the identified criteria. For an extensive evaluation example refer to [151].

6.3 Preliminary Summary

In the previous sections the concept of classical CO_2 abatement costs was explained, and methods were suggested to answer the question how industrial CO_2 abatement measures and transformation pathways can be evaluated holistically.

Core evaluation criteria for CO_2 abatement measures are emissions and costs associated with their implementation. Since the possibilities for balancing emissions and costs are diverse, defining balancing areas for both criteria is key to avoid their misinterpretation. In this dissertation emission balancing is confined to scope 1 and scope 2 CO_2 emissions. Upstream or downstream emissions along the value chain of industrial goods (scope 3) and other greenhouse gasses (e.g., methane) are not taken into account. The cost calculation is performed from two perspectives: the system and the investor perspective. The system perspective can be interpreted as a simplified approach to assuming a macroeconomic cost perspective. The investor perspective includes all cost components visible to the investor. Independent of the perspective, the costs for industrial transformation pathways and measures are expressed as additional or avoided costs with respect to the incumbent reference technology. Costs are not compared between scenarios since the integrated scenario process showed that the socio-political environment of the quEU and solidEU scenario worlds differ significantly, raising serious doubts over the interpretability of cost differences between so-called reference and climate protection scenarios.

Due to the importance of emissions and costs for the evaluation of abatement measures, the frequently used metric named *CO_2 abatement costs* was analyzed with respect to its advantages and disadvantages. The advantages of the metric mainly relate to the concise presentation of costs and potentials of abatement measures. While simplifying abatement measure evaluations is necessary to make this knowledge accessible to industrial and political stakeholders the classical CO_2 abatement cost concept is susceptible to misinterpretation. This results from limitations in three areas: data transparency, the methodological approach, and the non-consideration of macroeconomic and qualitative criteria.

To reduce the risk of misinterpretation due to the untransparent handling of data, five solutions were developed: 1) a detailed data appendix and discussion of assumptions is included 2) a consistent European data and calculation model is used to evaluate measures 3) measure and sector interdependencies are considered through the measure identification and selection method 4) the common representation of abatement costs in marginal cost curves is supplemented by the so-called matrix visualization and 5) sensitivity and uncertainty analysis are performed.

The methodological limitation of abatement costs refers to the fact that they do not consider intertemporal effects of measure implementation as well as energy system effects. To address this disadvantage the concept of dynamic abatement costs was introduced. Dynamic abatement costs capture the difference in costs and emissions incurred to the energy demand- and supply-side resulting from demand-side transformation pathways. In addition, an excursus focused on the effects of a high electrification scenario on the German energy system in 2030 is included in the results section. This analysis is used to exemplify what further energy system metrics should be considered during measure evaluation.

The question of which criteria in addition to costs and emissions should be taken into account for the holistic evaluation of abatement measures is addressed using an adapted multi-criteria analyses. For this purpose, the radar for the holistic evaluation of abatement measures was developed. It provides an overview of 24 evaluation criteria. These include so-called showstopper criteria, which indicate whether the implementation of a certain abatement measure should be reconsidered or avoided if grave disadvantages such as irreparable damages to soil or water quality are caused.

7 Evaluation of CO_2 Abatement in the European Industry Sector

In this section selected results for the transformation pathway analysis for quEU and solidEU (section 7.1) and individual measure analysis (section 7.2) are discussed. The evaluation in these sections focuses on dynamic abatement costs under consideration of their interpretative boundaries. Measures implemented in the quEU and solidEU scenario are not subject to exclusion according to show-stopper criteria. Furthermore, the system effects of high demand-side electrification and vRES shares are demonstrated for Germany in 2030 (section 7.3).

7.1 Transformation Pathways - quEU and solidEU

In this section, the results for the industrial quEU and solidEU transformation pathways are discussed. Selected quEU results have previously been published in [12]. The respective scenario independent input data is explained in section 3. The scenario storylines and quantification of scenario-dependent parameters can be found in section 5. Methodological details concerning the model landscape used to derive these results are detailed in sections 2 and 3. The cost and emission balancing approach are summarized in section 6. Results are described for the EU27+3. Cost evaluations are based on the Master's thesis [133], which was supervised by the author of this dissertation.

To provide an overview of the CO_2 emissions in quEU and solidEU in relation to the EU climate targets, historical direct CO_2 emissions and the scenario results for 2030 and 2050 are depicted in Figure 43.

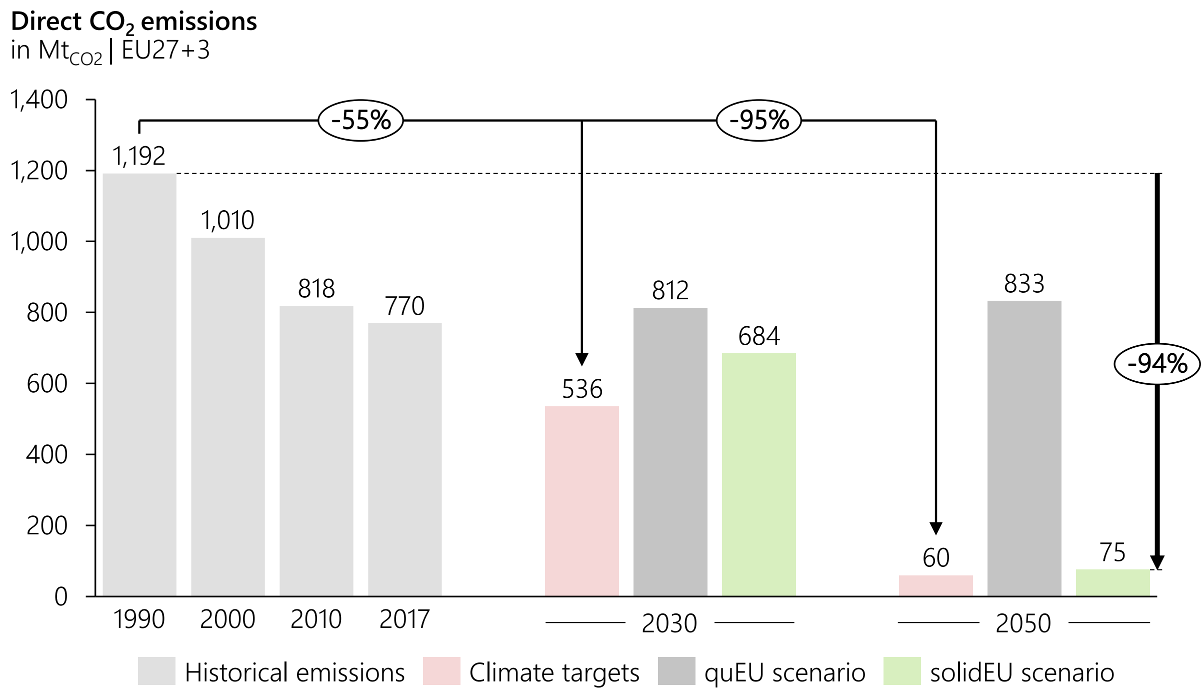

Figure 43: Emission reduction targets and direct emissions in quEU and solidEU, 2030 and 2050[120]

[120] Historical emissions from [155], industrial emission reduction targets are derived in [4, 5], they are not official regulatory targets.

The figure shows that, consistent to the quEU and solidEU scenario storylines, emission reduction targets are not met in quEU, while deep emission reduction in solidEU is achieved until 2050. It should be noted that quEU and solidEU are holistic energy system scenarios and that although the 2030 goal is not cleared in the EU27+3 industry sector, it is nevertheless met when considering the entire energy system [16]. In quEU, direct CO_2 emissions increase due to economic growth and despite efficiency measure implementation. By 2050 833 Mt_{CO2}/a are emitted, which poses an 8 % increase compared to 2017. This demonstrates that significant additional efforts are required to achieve emission reduction targets in the industry sector. Furthermore, it highlights that the socio-political environment in quEU is incompatible with achieving deep emission reduction.

In solidEU, emissions decrease by 86 Mt_{CO2} between 2017 and 2030. By 2050 annual industrial emissions are 75 Mt_{CO2}, which poses a 94 % decrease compared to 1990. Thereby it is assumed that the Covid-19 crisis does not exhibit a long-term impact in the EU27+3 on economic growth and therefore industrial emissions. The results presented in this section therefore do not capture effects of the corona crisis. To understand the developments resulting in the respective emission reduction, quEU (section 7.1.1) and solidEU (section 7.1.2) are analyzed in more detail with respect to final consumption, CO_2 emissions and cost development.

7.1.1 quEU - Final Consumption, Emission and Cost Development

In the quEU scenario no emission reduction targets exist. As described in section 5.2, the socio-political context in quEU is that anti-climate protection and financial incentives are insufficient to facilitate the technology readiness and implementation of deep emission reduction measures. The FEC development by energy carrier as well as the effect of economic growth and energy efficiency measures on FEC are depicted in Figure 44.

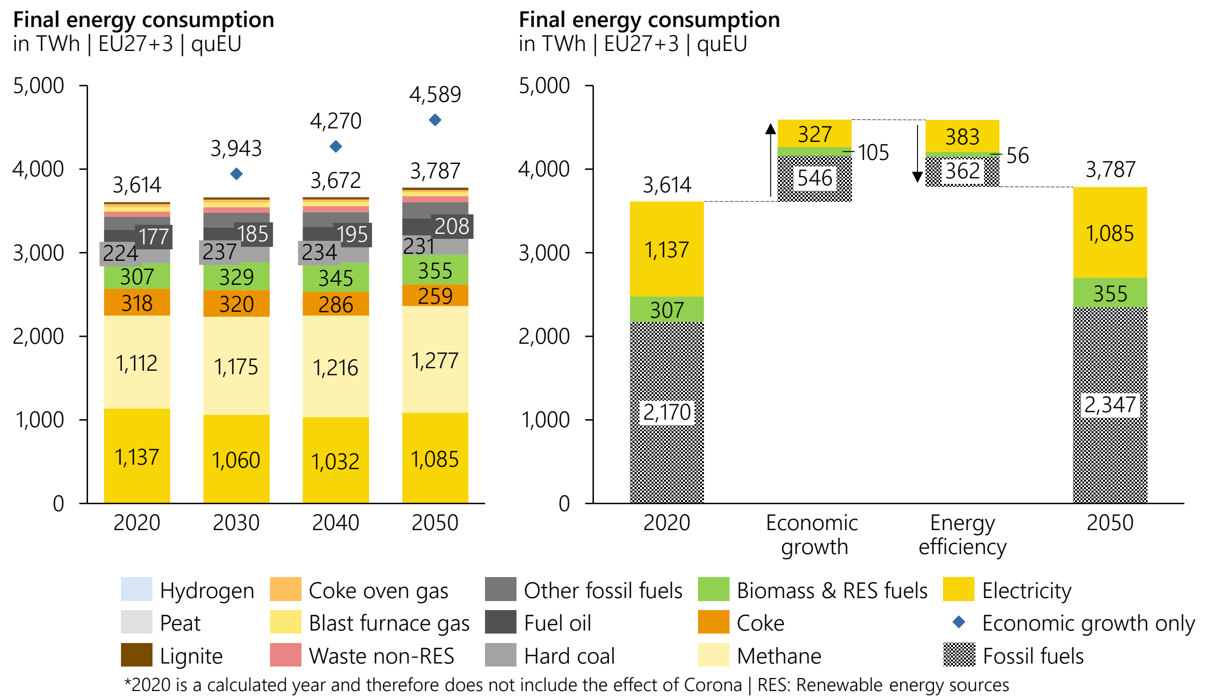

Figure 44: FEC by energy carrier and effect of economic growth and energy efficiency for quEU[121]

[121] The discrepancy between 2020 and 2017 emission values in section 3 result from the district heat split (cf. Section 4.1.2). All data is weather-independent.

The development of FEC by energy carriers in quEU shows that industrial FEC increases from 3,614 TWh to 3,787 TWh between 2020 and 2050. Since in quEU solely efficiency measures are implemented, the right hand-side of Figure 44 shows that efficiency measures cannot contain FEC increases due to economic growth. Nevertheless, they contribute to containing the FEC increase. Excluding efficiency measures 2050 FEC would amount to ~4590 TWh. Hence, these measures reduce FEC by ~0.6 % p.a. between 2020 and 2050, and thereby, electrical efficiency measures lead to an average gross reduction in electrical FEC of 1 % p.a. In addition, fuel efficiency measures cause an average gross efficiency increase of 0.48 % p.a. The difference between the electrical and fuel efficiency measures originates from CST efficiency measures, which predominantly address electrical FEC. In general, efficiency measures can contain FEC growth until 2040. However, the entire technical CST efficiency potential and a large share of the process measure potential are implemented by 2040. Absolute FEC growth therefore occurs mostly between 2040 and 2050. Despite the assumption that there are no significant structural changes to the industry sector in quEU, the share of electrical FEC decreases slightly until 2050, while biomass and methane shares increase. This results from strong electrical efficiency increases and growth in energy-intensive industry branches (e.g., lime, chemicals, paper), respectively. Energy carrier shares of primary steel energy carriers such as COG, BFG and coke decrease until 2050 since growth in primary steel production is low compared to the industry average.

In addition to the increase in FEC, economic growth in the chemical industry results in an increase of the modeled fossil feedstock for HVC, ammonia, and methanol production by 23 % between 2020 and 2050. This equates to an annual growth of ~0.7 % p.a. and is depicted in Figure 45.

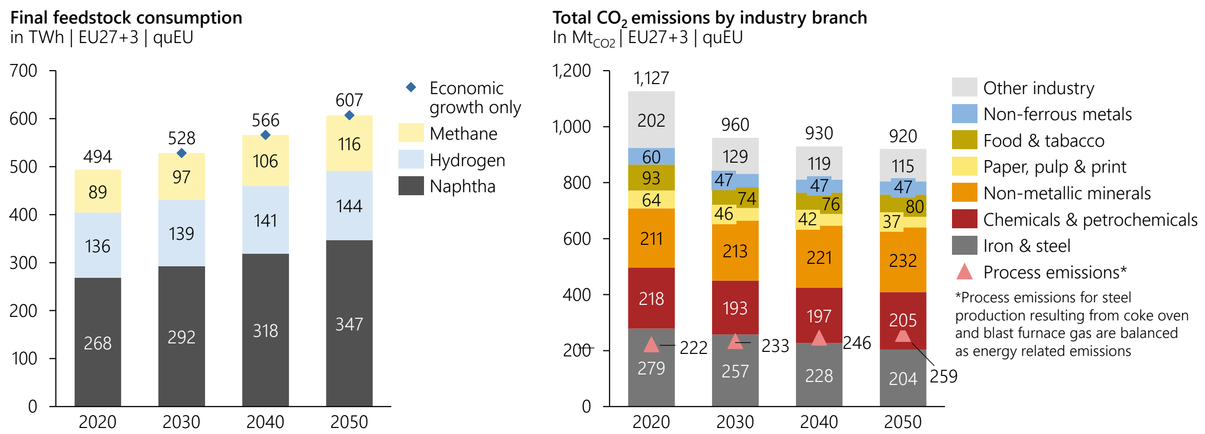

Figure 45: Final feedstock consumption and total CO_2 emissions in quEU

The right hand-side of Figure 45 shows that total CO_2 emissions in the industry sector decrease from 1,127 Mt_{CO2} to 920 Mt_{CO2} in the same time period. This results both from efficiency measure implementation and reductions in the emission factor for electricity in quEU [140]. Process emissions however increase from 222 Mt_{CO2} in 2020 to 259 Mt_{CO2} in 2050 since both drivers do not affect them. Furthermore, all industry branches except the non-metallic minerals industry experience emission reductions. This results from strong economic growth in the cement and lime industry, in which process emissions are a large source of emissions. The strongest emission reduction is exhibited in the iron & steel industry in which growth is stagnating, efficiency measures are implemented, and the electricity emission factor reduction leads to less indirect emissions from secondary steel production and steel casting.

Figure 46 shows the annual development of CO_2 emissions in quEU. Furthermore, the annual contribution of demand-side and supply-side measures to industrial emission reductions are highlighted. The figure reveals that especially between 2020 and 2030 emission reductions are driven by changes on the supply-side, which lead to a reduction of the average EU27+3 emission factor for electricity from 267 g_{CO2}/kWh_{el} in 2020 to 88 g_{CO2}/kWh_{el} in 2030. As shown in [16], this results from a drastic increase in installed RES capacity from 417 GW in 2020 to 1096 GW in 2030. The latter is mainly driven by additional on-shore wind and off-site solar power installations. Thereby the generated energy rises from 911 TWh to

2,349 TWh between 2020 and 2030. This corresponds to a RES share of total gross electricity consumption of 78 % in 2030. It should be noted that the increase in installed vRES capacity is purely market driven and occurs in absence of a GHG emission constraint [16].

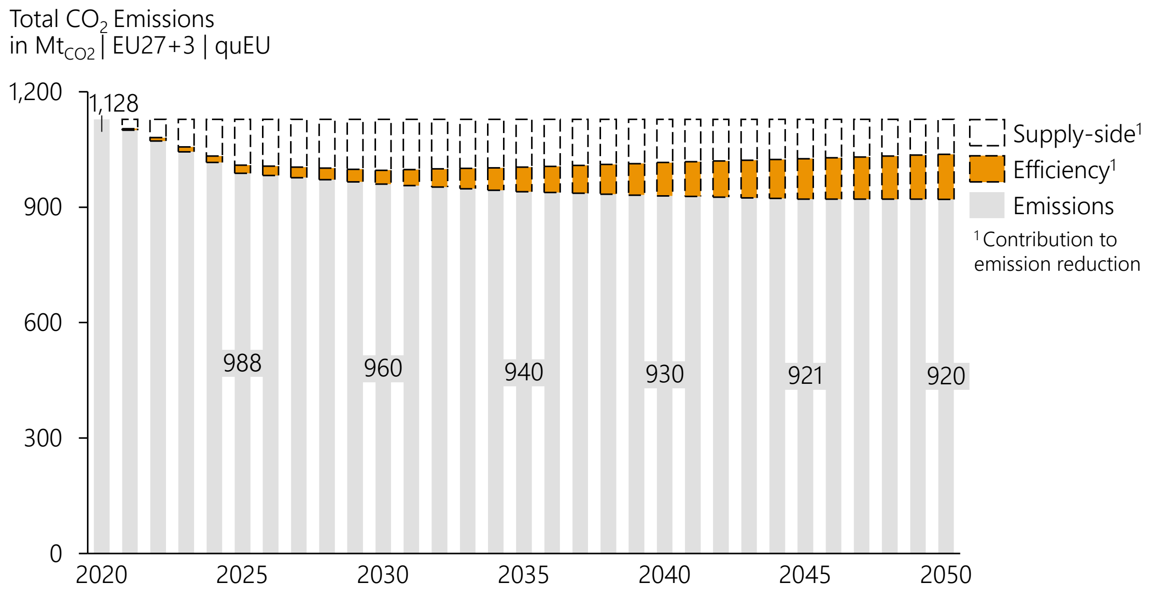

Figure 46: Annual total CO_2 emissions in quEU including CO_2 reduction by measure cluster

Figure 46 shows that the contribution of the supply-side reduces between 2030 and 2050 as the growth of vRES capacity slows, but this is insufficient for compensating the growth-related increase in CO_2 emissions. Between 2030 and 2050 the contribution of fuel efficiency measures increases. It captures two aspects: the emission mitigation from measure implementation for the existing production tonnages; and the effect that additional production tonnages are produced with the new efficiency standard. Hence, the effect of the implemented efficiency measures on emissions is also correlated with GVA growth.

Figure 47 depicts the additional annual and cumulative total cost in the quEU scenario compared to 2020.

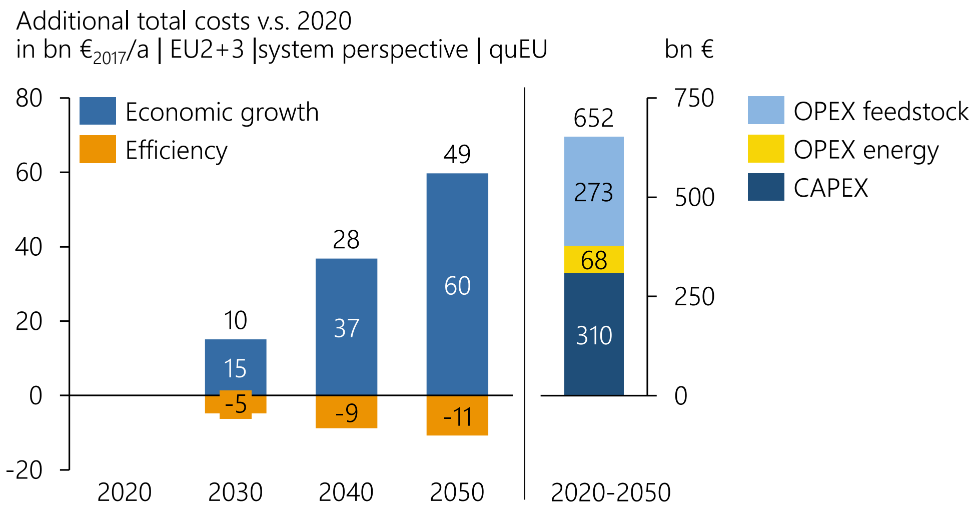

Figure 47: Additional total annual und cumulative cost in quEU[122]

[122] Own illustration based on [137].

The evaluation of annual additional costs shows that despite net cost savings from efficiency measure implementation, a cost increase occurs due to economic growth. Additional annual total costs increase over time and accumulate to 49 bn €$_{2017}$/a in 2050. Total cumulative costs between 2020 and 2050 amount to 652 bn €$_{2017}$. In comparison, the 2017 EU27+3 industrial GVA is ~2,700 bn €$_{2017}$. In quEU OPEX poses the lowest additional costs since efficiency measures contain FEC growth until the time period between 2040 and 2050. Total investment for efficiency measures accrue to 310 bn €$_{2017}$ over 30 years. However, as shown in the annual cost balance, efficiency measure implementation leads to avoided cost from the system perspective. The additional investment is consequently offset by OPEX energy savings. OPEX of feedstock is not affected by efficiency measure implementation and therefore leads to additional costs of 273 bn €$_{2017}$.

When considering the cost evaluation approach introduced in Section 6 it is important to reflect the purpose of ACs in the context of the quEU scenario. quEU is not a climate protection scenario. Both the socio-political context as well as the quantitative boundary conditions (e.g., absence of GHG emission reduction target in the supply-side optimization) do not reward the implementation of CO_2 abatement measures and therefore the emission difference is low compared to the costs which accrue in the scenario. When only evaluating direct emissions (cf. Figure 43) ACs cannot be calculated, since CO_2 emissions increase until 2050. Based on these arguments evaluating ACs for transformation pathways which are not aimed at achieving emissions reductions is not purposeful.

7.1.2 solidEU - Final Consumption, Emission and Cost Development

solidEU is a deep emission reduction scenario. As described in section 5 the socio-political environment is pro-climate-protection and deep emission reduction targets are set. Figure 48 shows the FEC development by energy carrier as well as the effect of economic growth and implementation of the different measure clusters on FEC in solidEU.

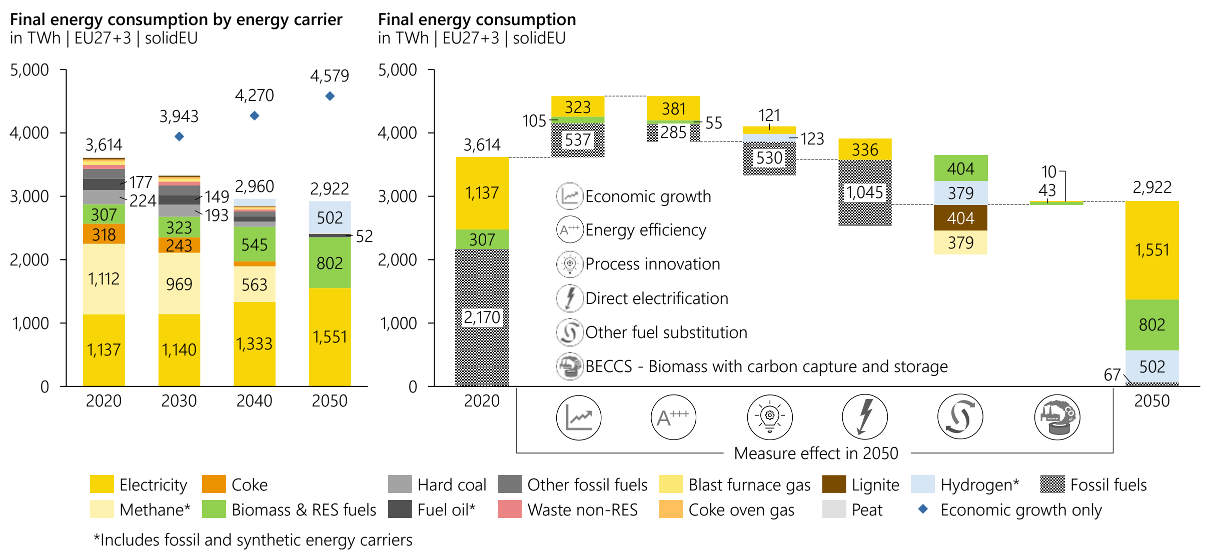

Figure 48: FEC by energy carrier and effect by measure cluster, solidEU[123]

FEC in solidEU decreases from 3,614 TWh in 2020 to 2,922 TWh in 2050. The reduction in FEC is caused by the implementation of efficiency and electrification measures. Industrial FEC in 2050 is dominated by electricity, biomass, and hydrogen. Between 2020 and 2050 electrical FEC increases by 36 % to 1,551 TWh. Main drivers for the increase in electrical FEC are the electrification of low temperature heat and process route changes in steel, HVC as well as glass production. The use of biomass and RES fuels usage grows

[123] The discrepancy between 2020 and 2017 emission values in section 3 result from the district heat split (cf. section 4.1.2). All data is weather-independent.

from 307 TWh to 802 TWh in the same time period. Main drivers for growth in biomass usage are the cement and lime industry as well as the substitution of fossil solid fuels through biomass, which commences in 2030. Thereby the sustainable biomass potential available to the EU27+3 industry sector in solidEU of ~860 TWh by 2050 (cf. section 5.2) is not exceeded. Furthermore, ~250 TWh of biomass and RES waste are used for BECCS in the cement and lime industry. The direct use of hydrogen for heat procurement leads to a FEC of 502 TWh_{H2} by 2050. Hereof 160 TWh are used in DRI & EAF steel production route. ~340 TWh are fed into hydrogen burners and CHP plants, thereby substituting natural gas for the provision of process heat. 80 % of this additional H_2 is balanced in the iron and steel, chemical and petrochemical, non-ferrous metal and non-metallic minerals industry branch. In addition to electricity, biomass, and hydrogen 52 TWh of synthetic fuel oil remain in 2050. The latter as well as 8 TWh of peat remaining in 2050 are the only source of direct energy related emissions in 2050.

The right hand-side of Figure 48 depicts the effect of economic growth and implementation of abatement measures on FEC in 2050, compared to 2020. It shows that economic growth would lead to an increase in FEC of 965 TWh. This is lower compared to quEU since it is expected that the demand and therefore production of lime in the EU27+3 decreases slightly as a result of the phase-out of primary steel. Efficiency measure implementation leads to a reduction of FEC by 721 TWh, which corresponds to an annual efficiency increase of 0.58 % p.a. between 2020 and 2050. The efficiency gain is lower compared to quEU since several measures are excluded due to interdependencies with process substitution measures. The latter result in an increase of the electricity (121 TWh) and hydrogen (123 TWh) FEC and a decrease in fossil fuel consumption (530 TWh). This change in FEC results from the process substitutions in steel, glass, HVC, MeOH and ammonia production. It should be noted that there is an energy efficiency gain resulting from these substitution measures which is however counteracted by the increase in feedstock demand as a result of HVC substitution (cf. Figure 49). Direct electrification in the low and medium temperature range results in an increase of the electrical FEC of 336 TWh and a reduction in fossil FEC of 1,045 TWh. This efficiency gain results from the deployment of industrial ground source heat pumps and electrode boilers. The substitution of coal and methane through biomass and hydrogen in measure cluster four results in an increase of 404 TWh and 379 TWh, respectively. Thereby it should be noted that these cross-sectional measures are designed to capture remaining fossil fuel consumption in industrial application for which the technology structure could not be elicited in this thesis. As discussed in section 3.3.2, it is plausible to assume that multi-fuel burners and hydrogen burners and turbines will enable the direct combustion of these fuels in a variety of industrial processes in future. However, further research into disclosing the existing technology structure at a European level is required to fully prove the accuracy of this assumption. Ultimately, CCS in lime and cement leads to an increase in electricity and fuel demand. Since these processes are mainly biomass and RES waste based by 2050, this results in the so-called BECCS measure.

In addition to FEC change, measure implementation and economic growth in solidEU result in changes to the feedstock consumption. The left hand-side of Figure 49 depicts the increase in final feedstock consumption from 494 TWh in 2020 to 885 TWh in 2050. The increase in production tonnages alone results in a 23 % increase in feedstock consumption until 2050. Process substitutions influencing the modeled feedstock consumption are the replacement of steamcrackers through the MTO and MTA process routes as well as hydrogen-based steel, ammonia, and methanol production. MTO and MTA process routes lead to a surge in MeOH consumption since the production of one ton of olefines requires ~2.8 t_{MeOH} and the production one ton of aromatics leads to an additional ~4.3 t_{MeOH} [51]. Since electrical steamcrackers are phased in as of 2040, 185 TWh of naphtha demand remain in 2050. As described in section 5.2.3, the synthetic naphtha and MeOH demand resulting from process substitution measures is covered by imports in solidEU. If produced domestically this could lead to an additional electrical FEC of 1,600 TWh_{el}. In addition to naphtha and MeOH the hydrogen-based production of ammonia, MeOH and steel results in 283 TWh of hydrogen feedstock consumption in the EU27+3. Total industrial solidEU hydrogen FC in 2050 is therefore 785 TWh, which presents a six-fold increase compared to today.

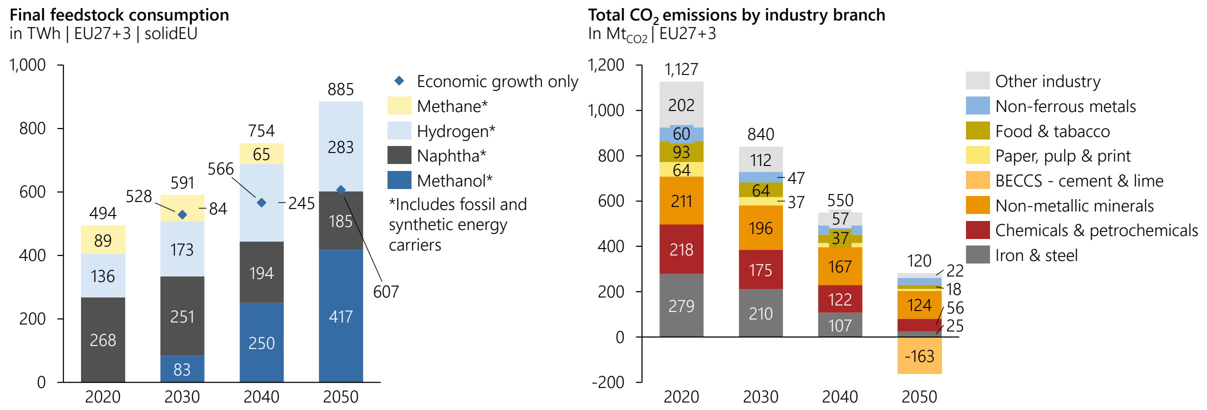

Figure 49: Final feedstock consumption and total CO_2 emissions in solidEU

The right hand-side of Figure 49 illustrates the development of total CO_2 emissions in the industry sector. Emissions decrease by ~90 % between 2020 and 2050. Thereby all industry branches in the EU27+3 contribute to achieving this reduction. The remaining 120 Mt_{CO2} emissions are split into ~75 Mt_{CO2} of direct process and energy related emissions as well as ~45 Mt_{CO2} of indirect emissions from electricity.[124] By this means direct emissions are net emissions, which are only achieved by allocating negative emissions from BECCS in cement and lime production to the industry sector. Through BECCS, process related as well as energy related CO_2 emissions in the lime and cement industry are stored. Since this entails capturing energy related emissions from sustainable biomass and RES waste, negative emissions are achieved in the process. If negative emissions are fully allocated to the cement and lime processes, the entire non-metallic minerals industry branch emission balance turns negative (-39 Mt_{CO2}). The critical contribution of BECCS to deep emission reduction in the time period 2045 to 2050 is also shown in Figure 50.

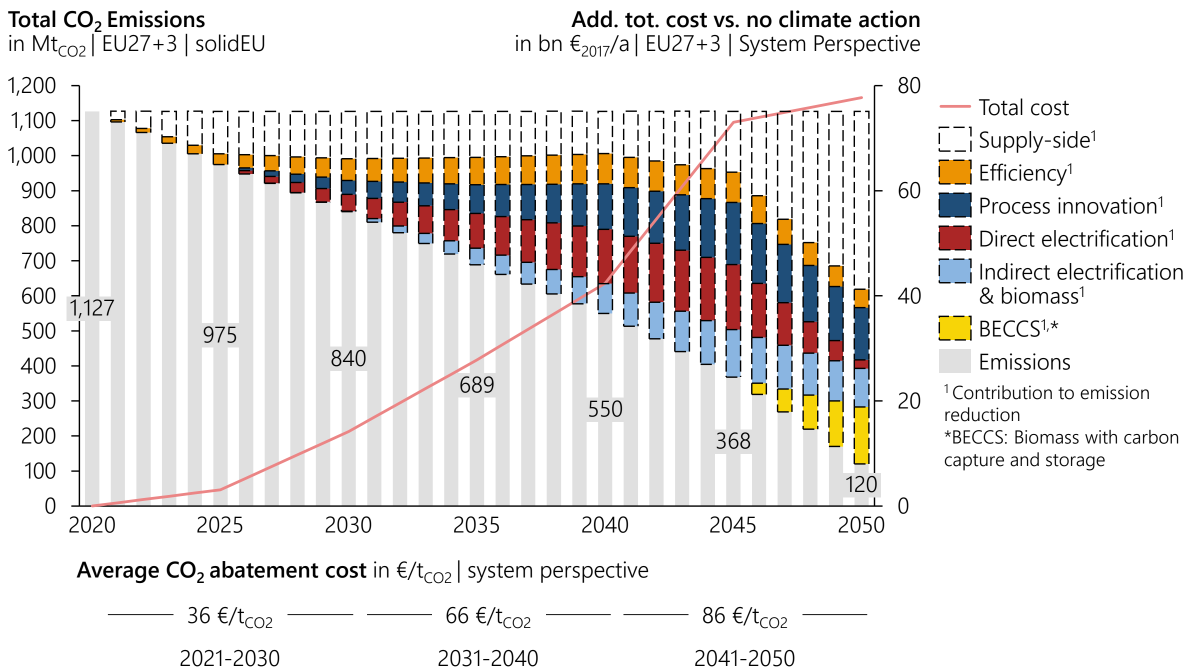

Figure 50: Annual total CO_2 emissions and costs incl. CO_2 reduction by measure cluster, solidEU

[124] Confer [140] for details concerning the generation mix on the supply-side.

Figure 50 depicts the annual development of CO_2 emissions and costs in solidEU including the contribution of each measure cluster and the energy supply-side to the achieved emission reductions. The figure shows that despite the continuous increase in measure implementation in all clusters, efficiency, process innovation, direct, and indirect electrification reach their maximum contribution to emission reduction before 2050. This results from the fact that the abatement potential of these measure clusters is linked to the supply-side through changes in the emission factors of the secondary energy carriers fuel oil, methane, electricity, and hydrogen. Through the supply-side transformation in solidEU, the emission factor of these energy carriers gradually decreases towards 2050. This results in a reduction of the abated emissions through efficiency measure implementation over time. For electrification measures, a similar effect occurs. Thereby the emissions abated through implementing these measures increase as the emission factor of electricity decreases, reaching a peak in 2045. Between 2045 and 2050, the share of emission-free SynFuels which are blended with natural gas and fuel oil is increased until a full substitution is achieved in 2050. This results in a stepwise decline of the methane and fuel oil emission factors.[125] Hence, by 2050, measures displacing methane and fuel oil do not contribute to the emission reduction, since they displace an already emission-free energy carrier.

Despite the reduced contribution to emission abatement, these measures are valuable to industrial actors because they reduce the required amount of expensive SynFuels. Thereby the incentives for measure implementation increase if energy carrier cost rises due to SynFuel usage. Since solidEU is a goal-based climate protection scenario, industrial actors do not face the decision whether to mitigate emissions, but if this is achieved by purchasing SynFuels or implementing alternative measures. The phase-in of SynFuels thereby affects both the costs of the reference technology and the abatement measure. Hence, the costs of the reference system increase as the GHG emission cap sinks. This in turn improves the cost evaluation of the abatement measure and explains why the increase in total annual additional costs, visualized in Figure 50, is slowed as of 2045.

Figure 50 shows an increase from an average of 36 €/t_{CO2} between 2021 and 2030 to 86 €/t_{CO2} between 2041 and 2050. Average ACs between 2020 and 2050 are ~75 €/t_{CO2}.[126] The increase in abatement costs over time in solidEU can be explained by the development of cumulative additional total costs and emissions and annual total additional costs by measure cluster as depicted in Figure 51. The left hand-side of the figure shows that cumulative emissions in solidEU exhibit a degressive development while cumulative costs increase progressively. The right-hand side of Figure 51 illustrates that costs accumulate slowly between 2020 and 2030 due to avoided costs from efficiency and direct electrification measure implementation. By 2030 total additional costs amount to 14 bn $€_{2017}$, while annual emission reduction is at 286 Mt_{CO2}, leading to AC of 50 €/t_{CO2}. The annual abatement cost peak is reached in 2045 with 96 €/t_{CO2}. Thereby annual additional costs are 73 bn $€_{2017}$ at avoided emissions of 577 Mt_{CO2}. Excluding abatement measure implementation in the remaining years until 2050, the annual and therefore cumulative additional costs would surge and exceed solidEU cost in 2047. The previously explained cost increase in the reference system however leads to a reduction in annual ACs between 2045 and 2050. Abatement measures therefore change roles and turn into cost saving measures.[127]

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[125] It is assumed that industrial actors purchase blended methane and fuel oil products once synthetic alternatives exist.

[126] In comparison, the European net-zero transformation pathway in [2] calculates 29 €/t_{CO2} between 2017 and 2030 and 118 €/t_{CO2} between 2041 and 2050. While these numbers are not directly comparable, they provide an indication that the AC results calculated in this dissertation are within a reasonable range. Also the 2050 AC difference appears meaningful since solidEU is a 95 % emission reduction scenario while [2] achieves climate neutrality by 2050.

[127] Results for the investor perspective support this. In 2050 additional *economic growth only* costs amount to 350 bn $€_{2017}$, while all implemented measures result in negative costs with a total of -224 bn $€_{2017}$. Total annual additional costs are therefore 126 bn $€_{2017}$. Due to taxes, levies, and surcharges on SynFuels, the value of measures avoiding their purchase increases.

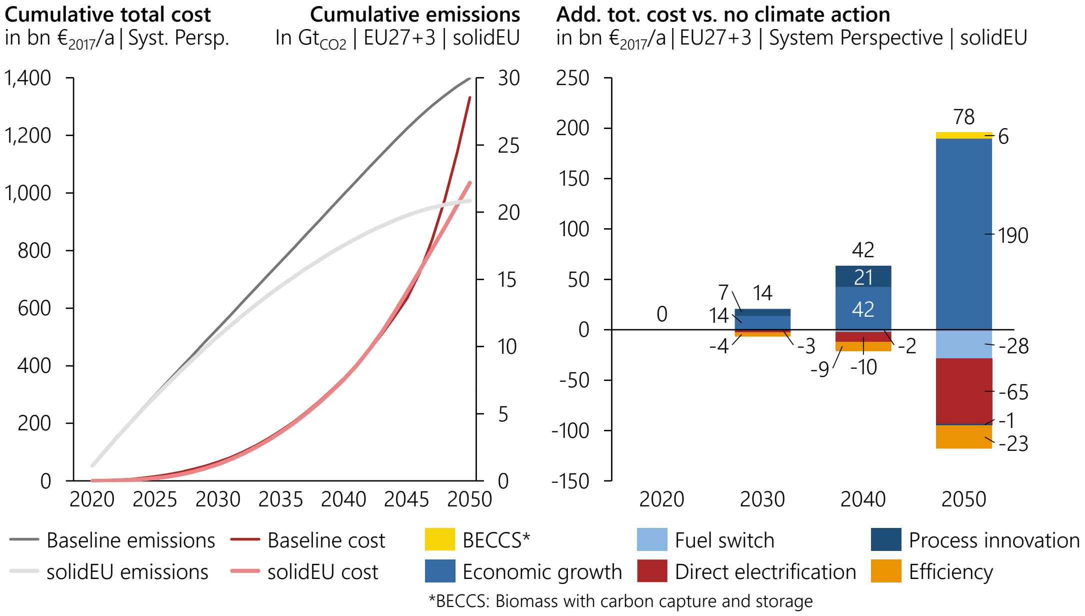


Figure 51: Total additional annual and cumulative costs and cumulative emissions in solidEU

The extent to which this is the case depends on the reference system. In a scenario world such as solidEU, where climate protection is enforced through the sociopolitical environment, avoided costs result from the implementation of electrification measures since the purchase of costly SynFuels is averted. This effect occurs close to the target year, because SynFuels are phased into the system as a last resort of emission reduction. Reflecting this finding against the background of long investment cycles in the industry reveals that the time between the necessary point of investment (for some technologies this is already between 2020 and 2030) and the payoff period is long.[128] In case policymakers fail to provide the respective investment security and incentives it is possible that the upcoming industrial investments cycles will result in reinvestments into incumbent process technologies. Especially in steel, HVC, lime, cement and other processes with long technology lifetimes this increases the risk for stranded assets. Thereby these investors face the challenge of comparing possible stranded asset costs to the risks involved with investing into a climate protection technology. [2] calculate the stranded asset value for their net-zero scenario to be 215 bn €$_{2017}$ by 2050. Thereby ~70 bn €$_{2017}$ accrue due to premature retirement around 2030, which is required to meet the 2030 emission reduction target. As shown in Figure 52 total cumulative additional investment in solidEU from the system perspective is 705 bn €$_{2017}$ for the time period 2021 – 2050. While the comparison is not robust it nevertheless indicates that stranded assets can lead to noteworthy additional costs for investors and should therefore be avoided.

Figure 52 shows the solidEU cumulative cost development by cost category, from the system as well as investor perspective. From the system perspective, cumulative energy costs are avoided compared to 2020. This mainly results from displacing costly fuel oil through electrification measures (cf. section 5.2.3 for energy carrier price developments). In line with the noticeable increase in final feedstock consumption, additional cumulative feedstock costs between 2021 and 2050 amount to 506 bn €$_{2017}$. In the same time period 705 bn €$_{2017}$ are invested into CO_2 abatement measures. Total additional cumulative costs of the solidEU transformation pathway are therefore 1036 bn €$_{2017}$ from the system perspective. From the investor perspective, both the cumulative CAPEX (1,152 bn €$_{2017}$) and OPEX (639 bn €$_{2017}$) gap between 2021 and 2050 are higher compared to the system perspective, leading to total additional cumulative costs of the solidEU transformation pathway of 1791 bn €$_{2017}$. Compared to the 2017 public and private total investment into industrial capital stock in the EU27+3 of 2,600 bn €$_{2017}$ this appears to be a manageable

[128] This argument takes into account that the aim is to reduce the risk of stranded assets in the industry.

additional cost [156, 157]. It should however be noted that large parts of the industry sector are exposed to a highly competitive environment, in which even slight cost increases can impede competitiveness on a global level.

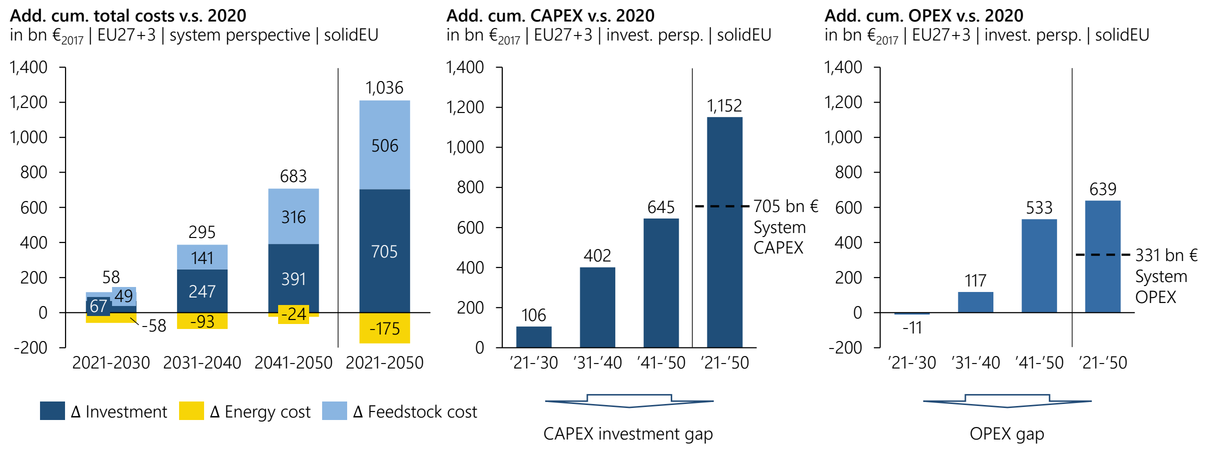


Figure 52: Cumulative additional cost from the system and investor perspective, solidEU

The analysis shows that feedstock costs and additional investment drive industrial transformation cost.[129] Thereby feedstock cost increases result predominantly due to the substitution of steamcrackers through MTO and MTA production procedures as well as the expected strong growth in the chemical industry of ~1 % p.a. It should be considered that this dissertation covers approximately 50 % of the transformation of relevant industrial fossil feedstock. Additional feedstock costs should therefore be interpreted as a lower estimate and further research is required to derive a full cost balance of feedstock transformation in Europe.

With respect to the additional cumulative investment into CO_2 abatement measures, Figure 52 shows that these costs increase from 106 bn $€_{2017}$ between 2021 and 2030 to 645 bn $€_{2017}$ between 2041 and 2050 from the investor perspective. Costs therefore rise as more innovative process and direct electrification measures are implemented. In the context of solidEU these measures are nevertheless implemented since it is assumed that a favorable investment environment for abatement measures exists. Furthermore, they lead to avoided costs as the target year is approached. In practice, additional CAPEX can however pose a barrier to measure implementation even if cost savings are achieved from a total cost perspective. Despite the relatively low cumulative additional investment compared to total annual industrial investment in the EU27+3 this cost component can act as a crucial barrier to measure implementation.

Energy-related OPEX on the other hand results in avoided costs from the system perspective.[130] This is a result of the comparably low prices for electricity and hydrogen in relation to the displaced fossil energy carriers. In particular, the difference to fuel oil leads to a noticeable reduction in energy carrier cost. Furthermore, solidEU exhibits low energy carrier costs since only comparably low amounts of SynFuels are used. The assumption that hydrogen burners and turbines will be available in the future permits this. It is important to note that an accurate assessment of transport infrastructure and storage costs for electricity, methane, hydrogen and SynFuels is not in the scope of this dissertation but can impact cost evaluations significantly.[131]

The analysis of cost components in the solidEU scenario reveals that CAPEX and feedstock OPEX drive costs of climate protection while energy-related OPEX reduces total costs. Considering the high uncertainty involved with cost calculations until 2050 the absolute values should however be treated with care.

[129] This true for both investor and system perspective.
[130] While not directly comparable, the German scenario [82] also exhibits negative cumulative OPEX.
[131] As described in section 5.2.3 losses resulting from hydrogen transport between countries are included in the cost evaluation. This does not substitute an energy system analysis in which also the demand for transport infrastructure is modeled and evaluated explicitly.

Independent of the uncertainty, the ad-hoc comparison of solidEU cost results with the European study [2] shows that ACs and cumulative additional costs are in a similar range.[132] It is therefore plausible to assume that additional costs of the industrial energy transition in the EU27+3 will in fact be relatively low when compared to current annual investment into industrial assets or GVA. This should however not belittle the challenge faced by the industry sector. Additional costs can potentially endanger the competitiveness of the domestic industry. This is especially the case if global efforts on climate protection lag behind European efforts. An idea for further research is consequently to expand the cost balance by further components such as material and personnel costs in order to assess the effect of the energy transition on the cost per ton of product. This in turn can serve as a starting point for assessing the effect of climate change mitigation on industrial competitiveness.

7.2 Individual Abatement Measures

The individual measure analysis serves to gain insights about abatement measures and to demonstrate methodological advancements explained in section 6.2.1. It is focused on measure implementation in Germany for solidEU. quEU is not discussed in this section, as the insights gained through individual measure analysis in this scenario are restricted to fewer measures and a comparably low dynamic in the energy system. A country-specific analysis is performed since core parameters such as energy carrier prices can vary significantly between countries. Furthermore, the decision situation for individual actors does not occur based on average European values. Figure 53 shows Germany's 2020 solidEU MACC for 113 selected technical abatement measures.

[132] In [2], ~432 bn $€_{2017}$ are calculated as additional CAPEX for the EU27 compared to no climate action at all. This is lower compared to 652 bn $€_{2017}$ for the EU27 in solidEU, but nevertheless within the same range when considering that these are cumulative costs over a time period of 30 years including costs for future technologies which have not been deployed at industrial scale today.

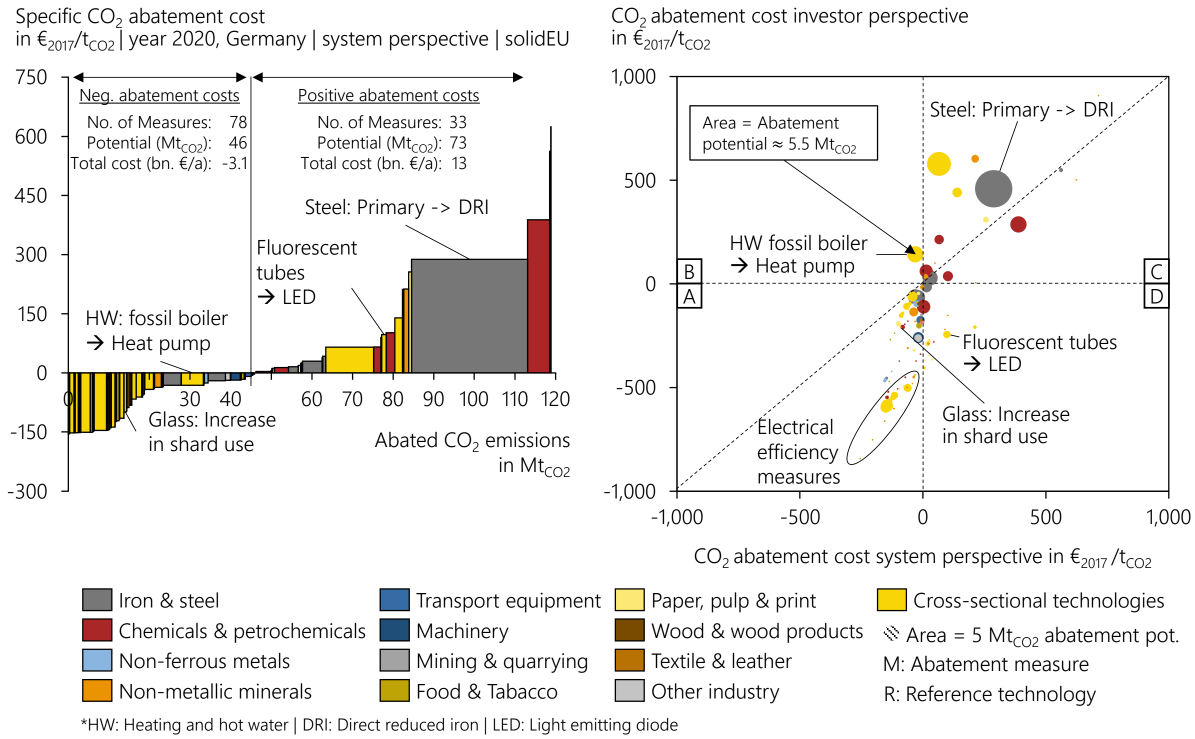


Figure 53: Total solidEU measure MACC and cost perspective matrix for Germany, 2020[133]

The MACC provides an overview of the abatement potential distribution between industry branches and CST as well as between positive and negative cost areas. It thereby indicates areas in which CO_2 abatement is, albeit all uncertainties, more costly than others. It cannot, however, be used to derive conclusions about the cost optimal order of measure implementation or total costs in solidEU. The following MACC based measure analysis should therefore be viewed as an indication of abatement costs from today's perspective, excluding the influence of system effects.

In Figure 53, measure interdependencies are considered in the input data, allowing for the aggregation of the depicted measure potential. As shown by the MACC, total technical measure potential in 2020 is 119 Mt_{CO2}, which equates to ~46 % of total German industrial emissions in 2020.[134] Excluding the costs associated with the system effects resulting from measure implementation, total annual implementation costs with respect to the underlying reference technologies accrue to ~10 bn € for all measures. Of the total depicted potential, 40 % comes at negative abatement costs (-3.1 bn €) from the system perspective. Half of this potential results from CST efficiency measures. Of these measures 15 are electrical CST efficiency measures with an abatement potential of ~14 Mt_{CO2}, thereby highlighting the importance of these measures for short to medium term emission reduction. In addition, CST efficiency measures are characterized by low technical complexity, high technology readiness and vast implementation experience amongst practitioners. ~73 Mt_{CO2} abatement potential are associated with positive costs. This area of the MACC is dominated by deep emission reduction measures. It shows that further R&D and implementation experience are required to achieve cost competitiveness with the reference technologies.

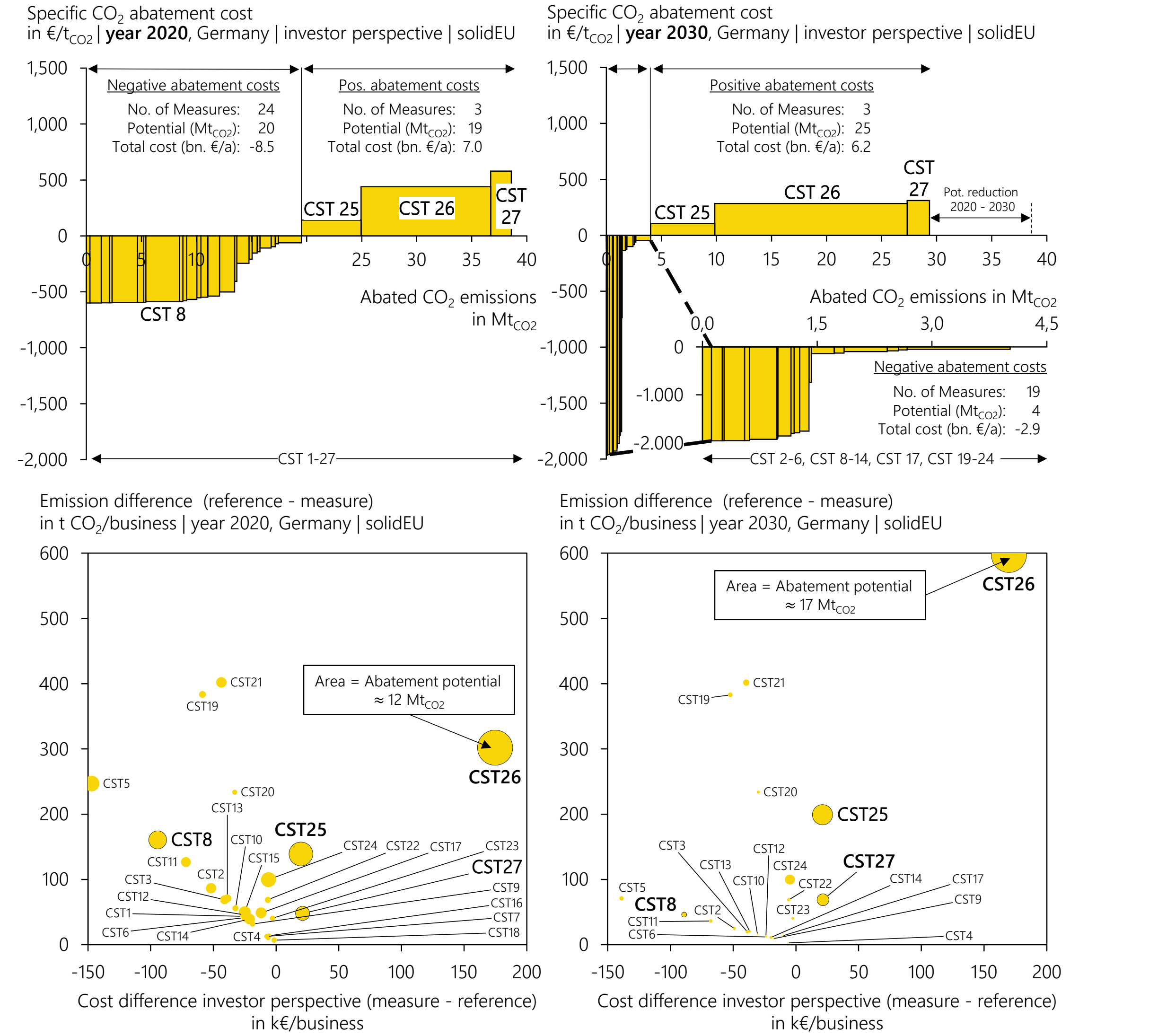
The cost matrix on the right-hand side of Figure 53 reveals that cost trends exhibited in the MACC curve are reinforced for the investor perspective. As described in section 6.2 the investor perspective includes

[133] From 131 selected measures, 2 endogenous CC, 14 efficiency and 4 measures with abatement costs higher than 750 €/t_{CO2} are not depicted. Industry branch specific energy carrier prices used for measure evaluation. CST measures evaluated using average energy carrier prices weighted by industry branch FEC. The earliest year of measure implementation is not considered in this visualization.
[134] Based on calculated SmInd EU value for 2020 which is 260 Mt_{CO2}.

taxes, levies and surcharges for energy carrier prices and considers investor opportunity cost through a higher discount rate. The analysis is structured according to quadrants A – D:

- **Quadrant A** shows that cost savings due to the analyzed electrical efficiency measures increase in the investor compared to the system perspective. This leads to higher negative abatement costs, indicating that abatement measure implementation leads to avoided costs for investors.
- HW procurement using heat pumps is the only measure in **quadrant B**. It exhibits avoided cost from the system and additional costs from the investor perspective. This results from the additional electricity price components, which increase the ratio of electricity to fossil fuel energy carrier prices. Policy measures aimed at adjusting this ratio could trigger increased fuel switch measure implementation. Thereby, it should be considered that electricity price adjustments can influence the cost efficiency of electrical efficiency measures. Fuel switch incentives could therefore simultaneously disincentivize efficiency measure implementation.
- **Quadrant C** shows that process substitution and fuel switch measures characterized by additional costs from the system perspective lead to even higher additional costs from the investor perspective. This is triggered both by higher opportunity costs for investors as well as additional energy carrier price components. This indicates that not only investor incentives for measure implementation, but also additional R&D and economies of scale are required to lower total costs of most deep emission reduction measures.
- **Quadrant D** shows measures such as the switch to LED, which exhibit negative investor and positive system cost. This results from higher energy carrier cost savings in the investor compared to the system perspective. It however does not imply that implementation of measures in quadrant D should be avoided, since the system cost perspective fails to reflect all ancillary benefits of measure implementation. For example: the system perspective does not assign value to measures for avoiding additional vRES expansion. In climate protection scenarios characterized by strong increases in electrical FEC, this can however mitigate the emission reduction challenge on the supply-side. The failure of abatement costs to capture system benefits creates a demand for further research aimed at defining a metric which attributes value to ancillary benefits. In [18] the author of this dissertation introduces the so-called *electrification decarbonization efficiency* as a metric to assess CO_2 abatement measures with respect to the additional or avoided electrical FEC per ton of mitigated CO_2. This could be a starting point for developing a combined metric reflecting the value of measures under consideration of additional criteria.

Since Figure 53 shows that CST measures exhibit a high potential for emission reduction of avoidable costs in 2020, these measures are analyzed in further detail in Figure 54.



CST1: Motor belt exchange
CST2: Optimized cooling distribution
CST3: Ventilation optimization
CST4: Lowering the pressure level
CST5: Control technical optimization electric drives
CST6: Ventilation - efficient drives
CST7: Ventilation - Belt exchange
CST8: High-efficiency drives
CST9: Compressed air control optimization
CST10: High-intensity discharge lamps → LEDs
CST11: Renewal of the ventilation system
CST12: Efficient air compressors
CST13: Efficient cooling unit
CST14: Lighting - control optimization
CST15: Server virtualization
CST16: Efficient IT devices
CST17: Fluorescent tubes → LEDs
CST18: Reduction of compressed air leakage
CST19: Heat recovery ventilation
CST20: Insulation of heat distribution
CST21: Heat recovery low temperature heat
CST22: Heat recovery cooling
CST23: Heat recovery compressed air
CST24: Increased efficiency of fossil boiler
CST25: Heat pump SH&WW
CST26: Electrode boiler 100-240 C
CST27: Heat pump <100 C

Figure 54: CST MACC and matrix visualization for Germany in 2020 and 2030

The figure shows 27 measures modeled as CSMs in SmInd EU. To demonstrate the effect of measure implementation and changes in emission factors and electricity prices on AC evaluation, 2020 and 2030 are compared. Thereby, 2030 shows the situation in solidEU and therefore exhibits dynamic AC. Furthermore, the investor perspective is depicted to display the boundaries of ACs as a metric for guiding measure implementation in practice.

The MACCs for 2020 and 2030 show that CST efficiency measures exhibit negative ACs (CST 1 – 24) while CST fuel switch measures (CST 25 – 27) lead to additional costs for investors. Comparing the 2020 and 2030 MACCs shows that changes in the solidEU energy system as well as measure implementation significantly impact the cost and potential of the depicted measures. It should be noted that, as opposed to static AC, the energy carrier prices and emission factors used to assess abatement measures in 2030 reflect the energy system configuration in the solidEU scenario. The relevant energy system parameter changes are the reduction in solidEU electricity prices and emission factors between 2020 and 2030, which are shown in Figure 34, Figure 35, and in the ISAaR dashboard in [140]. Total absolute emission reduction potential, for instance, decreases by 14 Mt_{CO2}.

Figure 54 shows that total measure potential of CST efficiency measures decreases by 15.5 Mt_{CO2} between 2020 and 2030. This results from the lower emission factor of electricity as well as measure implementation. The 2030 MACC contains five measures less than the 2020 curve since the potential of these measures is realized in this time interval. Furthermore, the reduction in measure potential is enhanced by lower electricity emission factors in 2030 compared to 2020. This highlights that the role of efficiency measures changes as emission reduction on the energy supply-side progresses. Hence, efficiency increases result in emission reductions as long as the respective energy carriers (e.g., electricity) are not emission free. In a largely emission-free energy system (e.g., solidEU in 2050), efficiency measures do not lead to noticeable emission reductions. In this case their role from a system perspective is to reduce the additional electricity demand and the expansion of emission-free electricity sources. From the investor perspective efficiency measures solely function as cost-saving measures. In this sense, efficiency measures will assume the role they fulfilled before climate protection became a priority.

Furthermore, CST efficiency measures exhibit drastic decreases in specific abatement costs, leading to ACs as low as ~-2,000 €/t_{CO2} in 2030. To understand this decrease, the matrix visualizations in the lower half of Figure 35 are analyzed with focus on CST 8 (high efficiency drives). In 2020 CST 8 exhibits the largest abatement potential of all CST efficiency measures in Germany. It exhibits a specific cost difference of – 94 k€/business and a specific emission difference of 161 t_{CO2}/business. This equates to abatement costs from the investor perspective of -590 €/t_{CO2} in 2020. By 2030 ACs drop to -1,900 €/t_{CO2}. At first, this indicates an improved business case for measure implementation in 2030 compared to 2020. However, analyzing the lower right hand-side of Figure 54 shows that both the specific cost (-89 k€/business) and specific emission difference (46 t_{CO2}/business) decrease compared to 2020. The drastic decrease in ACs is therefore a result of the lower specific avoided emissions and not lower specific costs. With respect to specific costs and emissions, circumstances for measure implementation are consequently worse in 2030 than in 2020, which results from a decrease in electricity prices and emission factors.

The analysis shows that the only conclusion which can be drawn from measures with negative ACs based on MACCs is that these measures lead to avoided costs. Comparisons between measures with negative ACs in the same year or between a measure in two different years are not meaningful. This results from the fact that the highly aggregated AC metric does not show if negative ACs are caused by low specific emission differences or changes in specific costs.[135] To analyze this, the additional information as provided by the matrix evaluation is necessary.

Thirdly, the comparison between 2020 and 2030 MACCs and matrix visualizations show that the absolute potential of fuel switch measures increases while their specific ACs decrease. Despite measure implementation of fuel switch CST in solidEU as of 2025, the potential of these measure increases by 6 Mt_{CO2} between 2020 and 2030. Simultaneously specific ACs of CST 25 – 27 decrease. Both aspects are influenced by lower electricity emission factors. In addition, lower positive ACs are induced by lower cost differences. Both aspects are visible in the matrix visualizations in Figure 54. The comparison between CST fuel switch and efficiency measures further emphasizes the contrary behavior of these measure types with respect to the development of electricity prices and emission factors.

Due to the high share of CST measures affected by electricity prices, the effect of a reduction in electricity prices is analyzed in Figure 55. Considering the importance of combining narratives and quantitative

[135] For positive ACs measure comparisons are viable since low specific emission and high specific cost differences lead to higher ACs.

evaluations, the sensitivity analysis portrays a hypothetical situation in which the investor electricity price is reduced by 65 €/MWh, which equates to the German EEG levy in 2021 [158].[136]

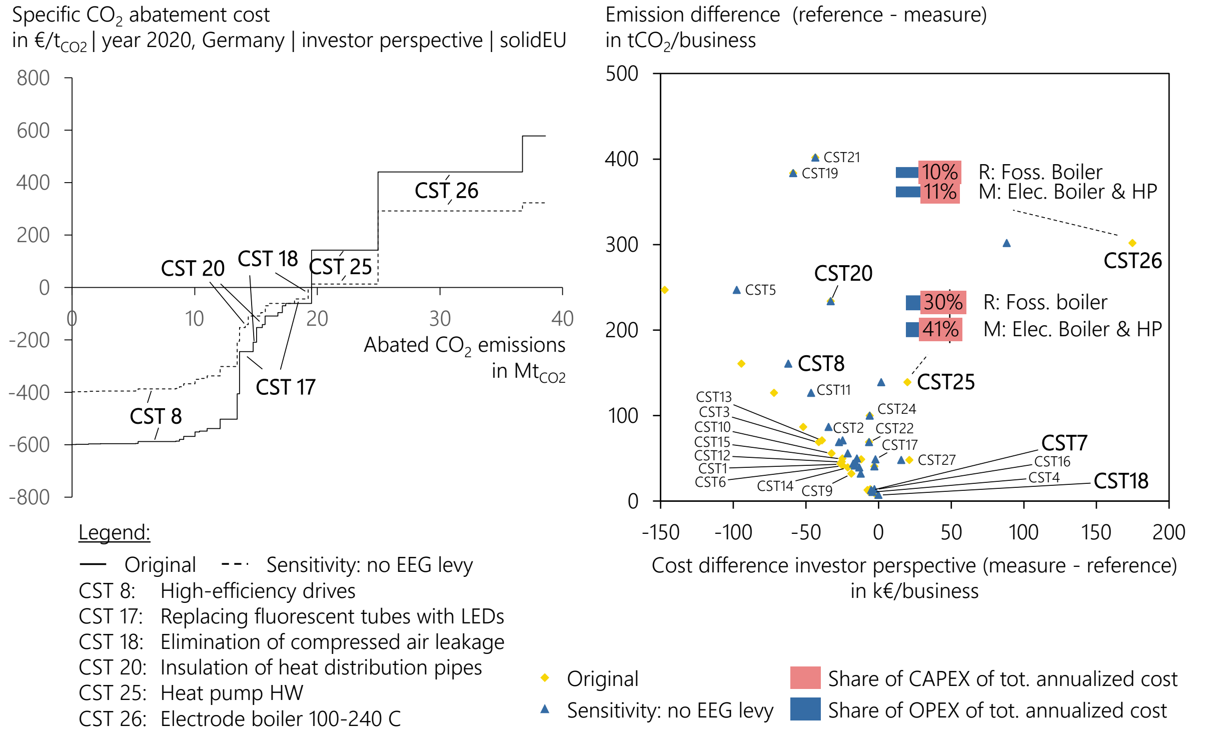


Figure 55: Effect of eliminating EEG levy on ACs of CST measures in Germany, 2020[137]

The MACC in Figure 55 shows that the reduction of the EEG levy leads to an increase in ACs for CST electrical efficiency measures (e.g., CST 17, CST 18) and a decrease for CST electrification measures (e.g., CST 25, CST 26). Fuel efficiency measures (e.g., CST 20) remain unaffected by this sensitivity. This results in position changes for CST 17 and CST 18 in relation to CST 20 in the MACC. The right hand-side of Figure 55 shows the effect of the sensitivity analysis on the cost difference of abatement measures (the emission difference is unaffected by price changes). With focus on CST 25 and CST 26, the matrix visualization shows that the change in cost difference of both electrification measures is more pronounced for CST 25. This results from the lower OPEX cost share in CST 25. Hence, the OPEX related sensitivity has a stronger impact on OPEX dominated measures. Including CAPEX and OPEX shares in the visualization matrix therefore serves as an indicator for the effect of certain sensitivities on AC. This in turn adds valuable information to MACCs in which uncertainty in ACs is not depicted.

The individual analysis of abatement measures shows that the methodological advancements to ACs improve their interpretability. Especially the risk of misinterpretation of negative ACs is reduced by including additional information. Furthermore, the exemplary sensitivity analysis highlights that visualizing CAPEX and OPEX shares of abatement measure costs can serve as an indicator for the effect of variations in certain cost components. In addition to methodological aspects the analysis emphasizes the importance of CST measures for industrial emission reduction. Thereby the contrary development of CST efficiency and electrification measures shows that the role of abatement measures changes over time.

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[136] Since CST measures are calculated based on average weighted industry branch specific electricity prices a differentiation of the EEG levy reduction by branch is not possible for CST measure evaluation.
[137] For visualization purposes not all measures are labeled. On the right hand-side each measure is only labeled once. The respective counterpart is clearly identifiable since the emission difference is constant and only cost differences result from the sensitivity.

7.3 Excursus: Energy System Effects in a High Electrification Scenario for Germany

The analysis of the quEU and solidEU transformation pathways is based on energy prices and emission factors which reflect the changes to the supply-side occurring in each scenario. By linking demand-side models such as SmInd EU to an energy system model such as ISAaR it is possible to capture the intersectoral effects between demand and supply-side. This is a prerequisite for the holistic energy system scenario evaluation and thereby for addressing one of the major critique points of static ACs (cf. section 6.2.1).

In both quEU and solidEU the supply-side developments are derived by performing a European market and grid simulation to determine unit dispatch, expansion demand and cross-border electricity flows [13, 16, 140, 159]. Each country is treated as a separate market zone and inter-country electricity trade is calculated in a simplified grid simulation, in which net transfer capacities between the EU27+3 are considered. Constraints due to downstream limited transmission network capacities are not considered. However, especially in deep emission reduction scenarios characterized by strong increases in gross electricity demand and electricity production from vRES, transmission network constraints can have a significant impact on the configuration and costs of the energy system. Since a European transport infrastructure analysis is not in the scope of this dissertation, the effect of high electrification rates and vRES expansion on the transmission grid and energy supply-side is therefore analyzed in an excursus for Germany in 2030.

The analysis should be viewed as a demonstration of how the effects of demand-side electrification rates in deep emission reduction scenarios on the supply-side can be evaluated. It was however not performed using the model landscape described in section 2. It presents an isolated analysis for Germany in 2030 and is solely performed by applying the energy system model ISAaR. Load data for the FEC sectors was derived using a simplified upstream calculation. This section provides a summary of the results of the analysis, which was previously published in [80]. It should however be noted that SmInd EU was designed to facilitate such analysis on a European level. To analyze the effects on the transmission network, FEC data in high timely and spatial resolution is required. It is therefore an obvious idea for further research to use quEU and solidEU demand-side transformation data to perform an energy system analysis under consideration of the transmission grid.

Electrification Scenario Development

The scenarios developed to showcase the effects of demand-side electrification and vRES expansion on the energy system are summarized in Table 18. The analysis entails comparing a reference scenario to two electrification scenarios with the same demand-side, but different supply-side configurations. The reference scenario is characterized by low demand-side electrification as well as low grid congestion. This scenario is compared to *Elec61* and *Elec75*. Both scenarios exhibit a gross electricity consumption including grid losses of 759 TWh in 2030. This poses an increase compared to the reference scenario of ~50 %. The latter results from the implementation of direct electrification measures in all FEC sectors (e.g., electric vehicles, glass production, heat pumps). The additional demand is predominantly inflexible electrical load, except for power-to-heat (P2H) modules in district heat networks. It is assumed that P2H can accommodate up to 20 TWh of electricity.[138] Elec61 and Elec75 differ with respect to the share of RES of gross electrical FEC.[139] In Elec61 this share is 61 %. Thereby it is assumed that the RES share from the reference scenario in 2030 is sustained despite the strong load increase. In Elec75 a 75 % share is assumed, which reflects an increase of vRES generation equal to the absolute load increase. Hence, Elec75 approximates emission-free electrification. In all scenarios the same reference grid for Germany is used. It is described in detail in [159].

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[138] However, the model does not allow for transmission network relief through P2H modules. This is an idea for further research.

[139] RES as opposed to vRES also include dispatchable renewable sources such as hydro power.

Table 18: Demand and supply-side electrification scenarios for Germany, 2030[140]

Parameter	Unit	2015	2030 Scenarios		
			Reference	Const. RES share electrification	RES covered electrification
CO_2-Price:	€/t_{CO2}	7.6	30		
Fuel Prices: (Oil/Gas/Hard Coal/Lignite)	€/MWh_{th}	(36/22/9/1.5)	(52/29/9.5/1.5)		
Fossil Capacity:	GW_{el}	87	59,0 (without reserve capacity)		
RES generation:	TWh_{el}	190	304	467	573
vRES Capacity: (Wind-Offshore/-Onshore/PV):	GW_{el}	(3/41/39)	(15/59/77)	(15/99/146)	(15/125/190)
Electrical. load (incl. grid losses)	TWh_{el}	554	499	759	759
District Heating (flexible P2H-load):		0	0	20	20
Transmission grid	-	-	Reference grid (low congestion)	Reference grid	Reference grid
Net RES Share (without curtailment):			~ 61 %	~ 61 %	~ 75 %
Scenario abbreviation:			*Ref61*	*Elec61*	*Elec75*

Each scenario is direct input to the energy system model ISAaR. The modeling approach and metrics used to evaluate the supply-side effects are described in the following section.

Modeling Approach and Evaluation Metrics

As described in section 2, ISAaR deploys a linear optimization algorithm to determine the cost-optimal unit deployment required to satisfy the load condition. In this analysis the calculation-intensive investment optimization is not considered. In case this results in a capacity gap, so-called *virtual generation units* are dispatched to cover the electrical load and indicate the demand for additional generation units, storage systems or demand-side-management measures. For this excursus ISAaR is first used to perform a European market and simplified grid simulation to approximate flow-based market coupling. Subsequently, the resulting electricity imports and exports are fixed and a market simulation for the German/Austrian region is performed. The result shows the dispatch of generation units in Germany and allows for the determination of so-called *market-driven curtailment*. The latter is defined as the overproduction of vRES excluding grid constraints (i.e. curtailment occurs because there is insufficient demand) [160]. Subsequently a grid congestion simulation is performed to derive the volume of redispatch and grid-driven curtailment (cf. [159] for methodological details). This last step is performed several times with slight adjustments to the transmission grid, to determine the degree of grid expansion required to reduce redispatch and curtailment in the electrification scenarios. The previously described model simulation runs are performed separately for the Ref, Elec61 and Elec75 scenarios. The results are then analyzed with respect to changes in curtailment, redispatch, the CO_2-coefficient of power generation, as well as grid expansion demand.

System Effects in a High-Electrification and High-vRES Scenario

Scenario results are structured into two parts: first generation and then transmission grid-related effects are discussed. Generation related results are shown in Figure 56. In the electrification scenarios the higher vRES feed-in leads to stronger fluctuations of the residual load compared to the reference scenario. In times of high electrical load and low vRES generation this leads to additional conventional power plant dispatch in Elec61 compared to the reference scenario (cf. graph a). Thereby it is important to keep in mind that the

[140] Previously published in [80].

RES share in both scenarios is the same. Additional conventional generation mainly originates from gas-fired power plants and accumulates to 24 TWh. In addition, the German-Austrian market zone turns from a net electricity exporter to an importer (+32 to −39 TWh). In the market simulation, these changes result in a reduction of the emission factor for electricity by ~14 % (cf. graph b). In case grid constraints are considered redispatch and curtailment of vRES increases, leading to less vRES integration and a lower reduction by only ~12 %. A similar effect is viewed in Elec75, where the reduction of the CO_2 emission factor is however stronger, since absolute vRES production is higher.

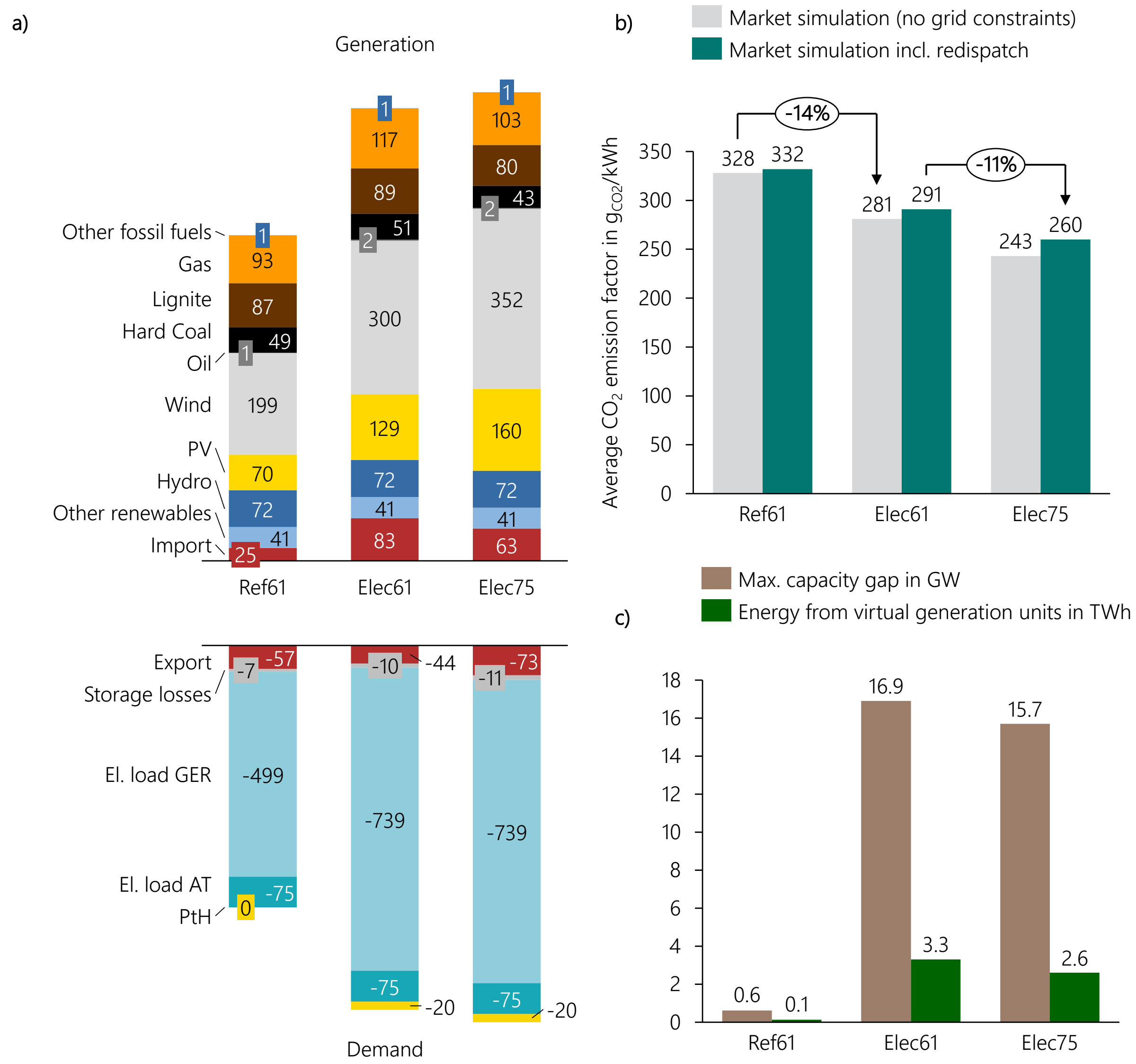


Figure 56: Scenario results Germany and Austria, 2030[141]

In both scenarios, coal-fired power plants are still dispatched, which explains the moderate reduction in the CO_2 emission factor. To enable deep emission reduction the expansion of vRES must therefore be flanked by the phase-out of conventional power plants. However, graph (c) shows that this would lead to a further increase in the capacity gap, which is already considerable in Elec61 and Elec75. This means that rapid electrification results in a dilemma: in order for electrification to lead to deep emission reduction conventional power plants need to be phased-out. Simultaneously the increase in load poses a barrier to

[141] Previously published in [80]. (a) absolute change in electrical power generation in TWh (b) CO2-coefficient of power generation in g_{CO2}/kWh (c) and generation capacity gap in GW and virtual electricity generation in TWh.

the required phase-out. Furthermore, it is unlikely that the capacity gap would be closed by additional gas-fired power plants due to relatively low full-load hours of ~200 h/a in both Elec61 and Elec75. This is shown by comparably low generation from virtual electricity production units in graph c of Figure 56. Hence, adding inflexible load to the system would result in challenges for the energy supply-side and increase the demand for flexibility.

Figure 57 shows upgraded transmission lines, redispatch and curtailment volumes in Germany and Austria in the reference scenario and Elec75. Higher vRES shares and electrical FEC consequently lead to heightened stress on the transmission grid and increase curtailment and redispatch volumes.

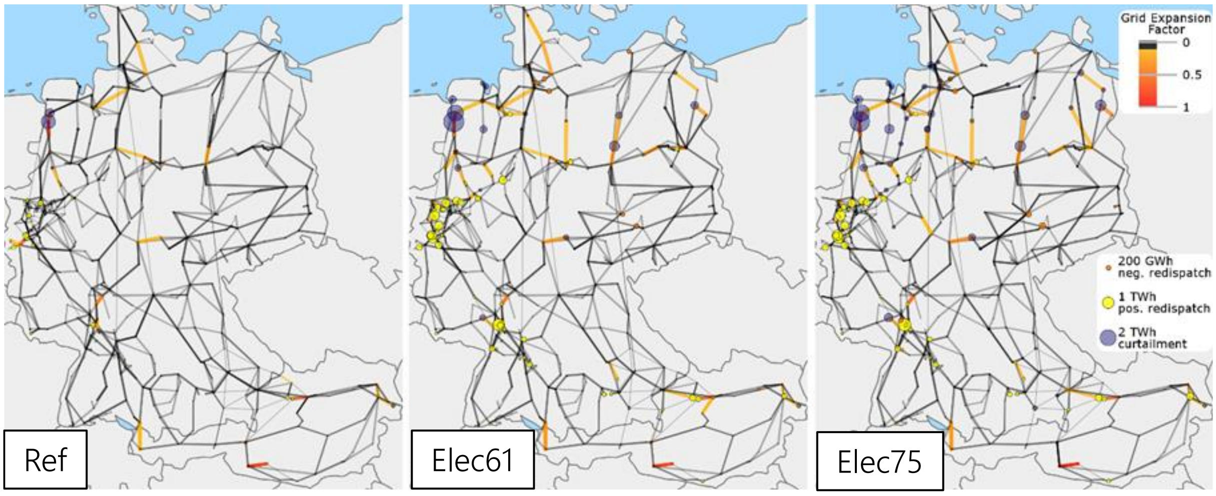


Figure 57: Transmission gird and congestion management volumes

The left hand-side of Figure 57 shows the almost congestion-free transmission grid in the reference scenario. In total 3.9 TWh of grid and market driven curtailment accrue in Ref. This equates to ~1 % of total RES production in this scenario. In Elec61 and Elec75 redispatch and curtailment volumes increase. In Elec61 grid-related curtailment amounts to 10.9 TWh while there is almost no market-based curtailment. This means that if the grid constraints are considered, electricity produced from vRES will be curtailed due transmission network congestions. Excluding grid constraints, flexible power-to-heat modules in district heat networks accommodate 19 TWh of electricity which reduces market-driven curtailment close to zero. Hence, the flexible electrical load fosters vRES integration. In Elec75 market driven curtailment amounts to 20.3 TWh and grid driven curtailment to 31.5 TWh. The installed flexibility options consequently cannot integrate the additional vRES in Elec75. This shows that additional electricity production from vRES increases the demand for flexibility in the energy system.

Nevertheless, grid driven curtailment in Elec75 still remains below ~2 % of total RES in Elec75. This is shown in Figure 58 in which curtailment is presented as a percentage of total RES in the respective scenarios. Furthermore, the figure shows how targeted grid expansions can lead to a reduction of congestion management volume in both electrification scenarios. In the case of Elec75 it is however questionable to what extent grid expansion is required as long as the market cannot accommodate the entire vRES production.

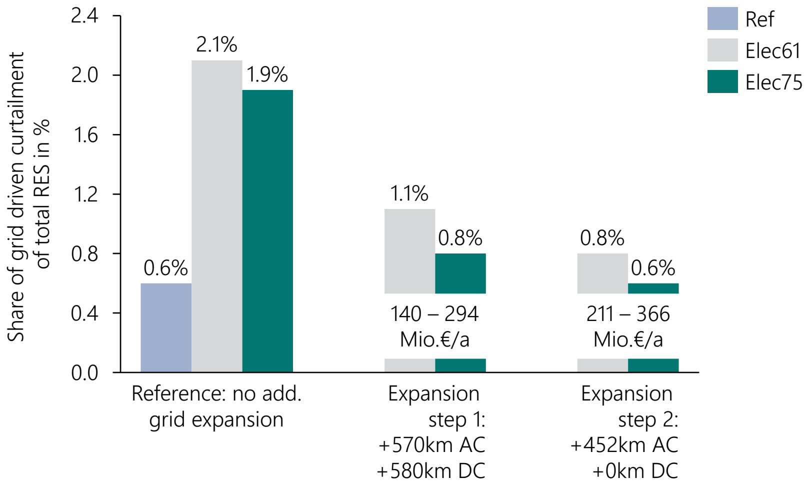


Figure 58: Grid driven curtailment as a share of renewable energy sources[142]

The excursus for Germany shows that including the transmission network as a boundary condition into ISAaR simulations can lead to changes in electricity generation compared to a market-only simulation. Furthermore, such analysis can uncover the demand for additional grid expansion demand and therefore reveal if a scenario reaches the physical limits of the existing transport infrastructure. In the case of the solidEU transformation pathway further infrastructure demands for CO_2 and hydrogen transport and storage exist. Similar to the analysis provided in this excurses, these demands need to be quantified and evaluated to gain a holistic understanding of the transformational costs and challenges on the supply-side. It poses a possibility for further research to perform such transport infrastructure analysis for the European energy system.

7.4 Preliminary Summary

In the previous sections the quEU and solidEU CO_2 abatement measures and transformation pathways were evaluated. The solidEU analysis was directed at answering the research question what CO_2 abatement costs result from the European deep emission reduction transformation pathway solidEU, and which cost components drive these costs. Furthermore, an excursus was provided which shows what further energy system metrics should be considered during measure evaluation, by analyzing the effects of a high electrification scenario on the German energy system in 2030.

The analysis of individual abatement measures in the context of the solidEU transformation pathway showed that the role of efficiency and electrification measures changes over time. As the emission factor of electricity decreases over time, the effect of electrical efficiency measures on emission reduction sinks. In turn, the importance of electrification measures rises. Efficiency measures, especially those addressing cross-sectional technologies, support emission reductions between 2020 and 2030. The contribution of direct electrification measures increases until 2045. As emission-free synthetic fuels are phased-in between 2045 and 2050 emissions of the incumbent reference processes decrease. Hence, the specific emission reduction of efficiency and direct electrification measures sink. The implementation of both measure types however results in avoided costs by 2050, since they reduce the amount of synthetic fuels required to achieve deep emission reductions. The role of these measures therefore changes from emission to cost reduction measures.

The results of the transformation pathway analysis shows that deep emission reduction in SolidEU leads to average cumulative CO_2 abatement costs for the EU27+3 of 75 €/t_{CO2}. Total direct and indirect CO_2

[142] Previously published in [80].

emissions could be reduced by 90 % by 2050, with respect to 1990, resulting in cumulative transformation pathway costs of 1 trillion $€_{2017}$ between 2020 and 2050. Thereof -175 bn € are avoided energy carrier costs, 705 bn € are additional investment and ~500 bn € are additional feedstock cost. Both additional investment and additional chemical feedstock consumption therefore drive industrial transformation cost. However, compared to the 2017 public and private total investment into industrial capital stock in the EU27+3 of 2,600 bn $€_{2017}$, these costs appear bearable. Nevertheless, additional costs must be evaluated against the background of the competitive pressure in the global industry sector.

The excursus for Germany shows that including the transmission network as a boundary condition into ISAaR simulations leads to changes in electricity generation compared to the market-only simulation. Electrification and vRES expansion increase the demand for grid expansions and therefore the dynamic costs of abatement measures. The analysis therefore shows that restrictions due to limited or currently still non-existent (e.g., European hydrogen backbone) energy transport infrastructure need to be quantified and evaluated to gain a holistic understanding of the transformational costs and challenges on the supply-side.

8 Conclusion and Outlook

In this thesis methods for the holistic evaluation of CO_2 abatement in consistent socio-technical scenarios for the European industry sector were developed and applied. This section is split into two parts: the first part outlines the insights gained throughout the process of developing and applying the respective methods, by providing answers to the research questions. The second part provides a critical reflection of the methodology and the resulting ideas for further research.

8.1 Answers to Research Questions

Research questions are answered in the order in which they were addressed throughout the dissertation.

How can technical CO_2 abatement measures for the industry sector be identified and quantified?

In section 3 a European data model was constructed in order to provide the necessary input data for modeling European transformation pathways. A core component of these transformation pathways is industrial CO_2 abatement measures. The identification and selection of abatement measures in the industry sector is challenged by its heterogeneity which results in the fact that not the entire industrial technology structure can be captured in model calculations. Consequently, for this analysis two preparatory steps were undertaken prior to measure identification: First, the European energy carrier and application balance was constructed to determine industry branches and applications which pose the largest CO_2 emitters. Resulting from this analysis six industry branches which cover ~80 % of total industrial CO_2 emissions were selected for in-depth analysis. Second, process balances for the most energy and emission intensive processes in each of the selected industry branches were established to identify which technologies needed to be addressed by abatement measures to facilitate deep emission reduction. Combined, the industry branch and process balances disclose the technology structure behind 78 % of industrial CO_2 emissions.

Based on the results of these preparatory steps, a method for the identification, selection, parametrization, and quantification for industrial abatement measures was developed and applied. Process specific abatement measures were identified based on literature research and subsequently validated by industry experts. To derive abatement measures for cross-sectional technologies, real primary data from ~2500 abatement measures calculated for companies in the scope of energy audits in Germany and Austria were evaluated. Ultimately, additional cross-sectional measures were defined to address the share of emissions for which the technology structure could not be elicited in this thesis.

The work performed in this dissertation shows that to identify and quantify CO_2 abatement measures in the industry sector, several steps aimed at coping with the heterogeneity and complexity of the sector are necessary. Furthermore, either the use of primary data or a combination of literature data and expert validation are required to reduce the uncertainty of techno-economic data for industrial abatement measures. The process also revealed that the possibility of modeling country specific differences between processes as well as the effect and applicability of abatement measures is impeded by the lack of such data. While obtaining average European values or ranges for parameters such as specific consumption values or savings for certain process and measures is possible, country-specific values are infrequent. Hence, the assumption used in this dissertation, that country-specific differences for process and abatement measure data are negligible, could neither be confirmed nor denied.

How can the European industrial energy and feedstock consumption be modeled in high temporal and spatial resolution?

To model industrial energy and feedstock consumption in high temporal and spatial resolution the industry model SmInd EU was developed. The model is structured into three modules: final consumption, regionalization, and load profiles.

The final consumption module is a hybrid bottom-up and top-down model which is used to derive annual, country, industry branch, application, and energy carrier specific transformation pathways for the time period 2017 - 2050. The model includes 13 industry branches, 14 energy and 4 feedstock carriers as well as 12 applications, 27 bottom-up modeled processes and 131 individual abatement measures. Transformation pathways are modeled at industry branch, process, and abatement measure level. The algorithm first deploys a so-called baseline calculation in which the effect of economic growth on the final consumption and process emission development is calculated. On top of the baseline calculation the identified CO_2 abatement measures are applied to derive the scenario-specific development of final consumption and process emissions. Energy related emissions can subsequently be calculated by scaling final energy consumption with the respective emission factors. The final consumption module in SmInd EU is designed to facilitate the scenario-based parametrization of transformation pathways. The results of the final consumption module are direct input for the regionalization module.

In the regionalization module the spatial resolution of annual industrial transformation pathways is increased from NUTS-0 to NUTS 3. The regionalization is based on a set of allocation keys. Thereby the final consumption of process applications in the energy-intensive industry is regionalized via industry sites. CST applications and parts of the non-energy intensive industry for which no specific industry site data is available are regionalized via employee shares by country and industry branch. To facilitate the regionalization via industry sites the European industry-site database is constructed. The latter is derived using a matching algorithm which combines industry-site data from the EU ETS and E-PRTR emission databases as well as process-specific research results.

Lastly, the SmInd EU load profile module disaggregates annual final consumption at NUTS-3 level to hourly load data. To do so, energy carrier and application specific synthetic load profiles are derived. Synthetic load profiles are calculated based on real load data collected in energy audits performed by FfE in Austria and Germany. For the applications heating and hot water, temperature-dependent load profiles from the tertiary sector are used.

The combination of results from the final consumption, regionalization and load profile modules enables the analysis of final consumption and consequently emissions for all 1348 NUTS-3 regions in Europe, in hourly resolution. It therefore provides the possibility to model the industrial energy transition in a specific region as well as in the EU27+3 as a whole. Furthermore, the modular structure allows the flexible and independent adaptation of the individual components, which facilitates future model expansions.

How can qualitative context scenarios be translated into a quantitative framework to derive a consistent socio-technical European deep emission reduction scenario for the industry sector?

To determine consistent socio-technical scenarios a link between qualitative CIB-based context scenario construction and quantitative modeling was established. Thereby an existing gap in the integrated scenario literature is filled through the so-called *From Word to Value* process, which was developed in this dissertation. The latter structures the matching of qualitative and quantitative scenarios. At the heart of the five-step procedure lies the descriptor-parameter-matrix in which scenario descriptors are connected to scenario dependent model-exogenous parameters. Through this connection direct and weak links between descriptors and parameters can be identified. By eliciting the connection between descriptors and parameters the traceable and consistent quantification of parameters is facilitated. Despite the structured link between both scenario types, the subjectivity involved in quantifying parameters cannot be eliminated fully. While the procedure limits the risk of inconsistent quantifications, a direct translation of qualitative storylines to quantitative scenarios is not possible.

The developed integrated scenario process was then applied to derive two holistic energy system scenarios: quEU and solidEU. The process can be described as having a medium-degree of integration between qualitative and quantitative scenarios. Semi-annual meetings between the author of this dissertation and the context scenario construction team at KIT ITAS resulted in the possibility to adjust descriptors and parameters, without restricting each discipline through overly precise matching. By applying the *From Word to Value* procedure, SmInd EU and the descriptor set used to derive the quEU and solidEU scenario storylines were matched. This showed that the degree of detail in quEU and solidEU concerning the industry sector was insufficient for deriving exact industry branch or process specific transformation pathways. However, the context scenario provided sufficient detail to support the quantification of industry specific aspects in the spirit of the storylines.

The development and application of the integrated scenario process also revealed that comparisons between scenario worlds are at the least extremely difficult. Numerous energy political studies at the European and German level however frequently compare climate protection and so-called reference scenarios, and go as far as calculating cost differences to derive conclusions about additional costs of climate change. The solidEU and quEU development process, however, shows that the socio-political environment required to trigger quantitative developments leading to climate protection differ significantly from scenarios in which targets are not achieved. This suggests that comparisons between scenarios with completely different underlying drivers and assumptions are not meaningful. Since the aim of most energy political scenarios is to uncover plausible transformation pathways, this author suggests using the status quo as a point of comparison, since it is easily interpretable and does not disguise scenario results through a complicated comparative analysis.

How can industrial CO_2 abatement be evaluated holistically and what further criteria are relevant for the evaluation of industrial CO_2 abatement measures besides cost and potential?

To determine how industrial CO_2 abatement measures and transformation pathways can be analyzed holistically, the concept of CO_2 abatement costs was revisited. Three main areas of limitations of classical abatement cost evaluations were identified: data transparency, methodological approach, and macroeconomic and qualitative criteria.

The data transparency category addresses the issue that abatement costs are a strongly aggregated metric which does not disclose sufficient information to avoid the risk of misinterpretation. This is especially the case when abatement costs are visualized in so-called abatement cost curves. To reduce the risk of misinterpretation five adaptations were proposed and implemented in this dissertation: first, a detailed data appendix and explanation of assumptions is provided to improve data and result transparency. Second, a consistent European data model and the industry model SmInd EU were used to evaluate the identified abatement measures and resulting transformation pathways. Hence, the evaluation is not skewed by differences resulting from underlying data or variations in the calculation method. Third, measure interdependencies were considered in the measure identification and selection method, to avoid overestimating the total abatement potential. Fourth, the supplementary matrix visualization was developed in order to provide additional information on the cost structure of the measures, as well as interpretation support for negative abatement cost. Furthermore, it enables the comparison of abatement costs from different cost perspectives. Lastly an exemplary sensitivity analysis was provided to showcase the effect of electricity price reductions on cross-sectional-technology abatement cost measures. The number and kind of drawbacks with respect to data transparency show that abatement costs and their visualization in abatement cost curves are prone to misinterpretation. Policymakers, researchers, and practitioners should therefore consider the provided solutions to counteract data transparency issues.

The methodological limitation of abatement costs refers to their static nature. Classical abatement costs are snapshots in time and space, therefore they do not represent path dependencies and they fail to capture the system effects of measure interpretation. To address these disadvantages the concept of dynamic abatement costs was introduced and applied in an individual measure as well as transformation pathway analysis for the EU27+3 and a time horizon between 2017 and 2050. In addition, an excursus for the evaluation of system effects caused by the implementation of direct electrification measures was performed for Germany. The methodological advancements reveal that dynamic abatement costs as well as additional metrics are necessary to capture the effects of demand- and supply-side effects resulting from measure implementation. However, these methodological advancements are resource-intensive and cannot be performed in every case.

Lastly, an adapted multi-criteria-decision analysis approach was developed and executed to identify relevant criteria for industrial abatement measure evaluation through an unbiased review of multi-criteria-analysis literature with focus on industrial abatement measure evaluation. The developed radar for the holistic evaluation of abatement measures thereby provides an overview of 24 evaluation criteria. These include so-called showstopper criteria, which indicate whether the implementation of a certain abatement measure should be reconsidered or avoided if grave disadvantages such as irreparable damages to soil or water quality are caused. The criteria listed in the radar provide an overview of the variety of criteria which can impact the evaluation of abatement criteria. It also shows that costs and emission reductions are important, but not the only criteria with practical relevance to abatement measure implementation.

Through the identified methods aimed at improving the concept of classical abatement costs, an approach to a more holistic analysis of CO_2 abatement was developed. Furthermore, it became clear that capturing all facets of measure evaluation using a single metric such as abatement costs is not possible, and that further research is required until a truly holistic analysis of abatement measures can be achieved.

What are the CO_2 abatement costs of a European industrial deep emission reduction transformation pathway, and which cost components drive these costs?

The solidEU transformation pathway poses an ambitious socio-technical transformation pathway which leads to 94 % direct emission reduction in the EU27+3 industry sector by 2050 with respect to 1990. Thereby the implicit industrial 2030 target is not met despite ambitious technology exchange rates in all industry branches and application areas. This highlights that even in scenarios in which there are no socio-political constraints to the industrial energy transition, investment cycles as well as the technology readiness of key emission reduction technologies pose a threat to achieving intermediate emission reduction technologies. The analysis also shows that electricity, hydrogen, and biomass will become the industrial energy carriers of the future. Thereby the emission reduction in the transformation pathway depends on the provision of almost emission-free hydrogen and electricity as well as an intersectoral biomass shift from households and transport to the industry sector. This in turn shows that supply-side developments need to be taken into account during measure evaluation, since they are a key enabler for deep emission reductions.

This is further highlighted by the exemplary evaluation of the effect of high electrification rates and vRES expansion on the transmission grid and energy supply-side for Germany in 2030. The analysis indicates that in comparison to a purely market-based analysis, restrictions due to limited transport infrastructure can affect both costs and emissions along transformation pathways. While this analysis is not performed for solidEU, it shows that the holistic evaluation of measures requires supply-side analyses which consider energy transport infrastructure.

With respect to costs, the evaluation of the solidEU transformation pathway showed that average cumulative abatement costs for deep emission reduction between 2020 and 2050 in the EU27+3 are ~75 €/t_{CO2} from the system perspective. Total cumulative additional transformation costs between 2020 and 2050 and from a system perspective are approximately 1.04 trillion $€_{2017}$. Thereof -175 bn € are avoided energy carrier costs, 705 bn € are additional investment and ~500 bn € are additional feedstock cost. Both additional investment and additional chemical feedstock consumption therefore drive industrial transformation cost. However, compared to the 2017 public and private total investment into industrial capital stock in the EU27+3 of 2,600 bn $€_{2017}$, these costs appear bearable. Nevertheless, additional costs have to be evaluated against the background of the competitive pressure in the global industry sector. Further analysis is thus required to provide insights into how the additional costs affect the costs of production and to what extent this poses a threat to competitiveness.

The analysis of abatement costs in the solidEU scenario world shows that industrial actors can avoid certain costs by engaging in climate protection as the target year approaches. In a scenario world such as solidEU, where climate protection is enforced through the sociopolitical environment, avoided costs result for measures which reduce the demand for costly SynFuels (e.g., direct electrification). This effect occurs close to the target year, because SynFuels are phased into the system as a last resort of emission reduction. Reflecting this finding against the background of long investment cycles in the industry reveals that the time between necessary point of investment (for some technologies this is already between 2020 and 2030) and the payoff period is long. Considering the volatility of political decision making it is therefore clear that industrial investment can only be encouraged and expected if a reliable investment frame is provided. In the best case, this is an honest and irrevocable commitment to achieving deep emission reduction targets, as is the case in solidEU. In the real case this is a set of policy mechanisms such as carbon contracts for difference which reduce the investment risk for industrial actors. In case policymakers fail to provide the respective investment security and incentives the risk for stranded assets increases, which can lead to noteworthy additional costs for investors.

The individual analysis of abatement measures in the context of the solidEU transformation pathway showed that the methodological advancements to abatement costs improve their interpretability. In particular, the risk of misinterpreting negative abatement costs can be avoided by supplementing or substituting abatement cost curves through the matrix visualizations. In addition to methodological aspects the analysis emphasizes the importance of CST measures for industrial emission reduction. Thereby the analysis revealed that the role of efficiency measures changes over time. As emission reduction on the energy supply-side progresses, the effect of efficiency measure on emission reduction diminishes. While these measures strongly support emission reductions between 2020 and 2030 in solidEU, they are mainly cost saving measures by 2050. Also, the role of direct electrification measures changes as a result of the emission reduction on the energy supply-side. Thereby, their potential for emission reduction increases between 2020 and 2045 as the electricity supply is decarbonized. As emission-free synthetic fuels are phased-in between 2045 and 2050 the emissions of the reference technology for direct electrification measures decrease. Thereby the specific emission reduction of direct electrification measures decreases. By 2050 measures replacing methane and fuel oil therefore only lead to cost, but not emission reductions.

8.2 Critical reflection on developed methods and ideas for further research.

Throughout this dissertation a variety of assumptions were made to reduce the scope of the analysis to a manageable degree and cope with data unavailability and uncertainty. Furthermore, methods were developed which serve the purpose of this thesis but could be developed further to provide additional insights into the European industrial energy transformation and scenario analyses in general. In this section these assumptions and methods are reflected critically and ideas for further research identified.

European Industrial Data Model

The European energy carrier and application balance builds the basis for the transformation pathway analysis in SmInd EU. The accuracy of the calculation results consequently depend on the accuracy of this balance. Since the balance assumes that CST shares in all countries exhibit the same share as in Germany, inaccuracies with respect to th e final energy consumption shares of cross-sectional-technologies are likely. Furthermore, the process heat application shares are based on literature data with the base year 2012. The starting year for calculations in this thesis was 2017. While the industry structure did not change fundamentally in the five years between the share calculation and the base year, inaccuracies are nevertheless certain. It is expected that these uncertainties will increase as the industrial energy transition accelerates. Further research should therefore focus on providing annual updates of the energy carrier and application shares in each country, so that European data models such as SmInd EU base their calculations on data reflecting the true structure of each countries industry sector.

Process level data used in this thesis is country specific where literature sources provide the possibility for such differentiation. This is however not the case for most processes. While it is feasible to assume that industrial processes are similar across Europe, further research should be devoted to eliciting the exact and country-specific technology structure. This includes the age structure of industrial processes as well as specific energy consumption. Thereby the age structure of the existing technology stock is critical for calculating the risk and cost impact of stranded assets. In addition, information for the modeling of further industrial processes is required to model more accurate transformation pathways with respect to the ~20 % of industrial emissions for which the technology structure was not disclosed in this dissertation.

On the abatement measure level, high uncertainties with respect to all techno-economic parameters exist. Concerning cross-sectional technology efficiency measure data, further research should focus on identifying country-specific differences in the application factors. Furthermore, direct electrification measures were modeled as cross-sectional-measures in this dissertation. These technologies could be parametrized industry branch specific, in order to derive more accurate transformation pathway results. With respect to the innovative processes and carbon capture measures deployed in solidEU, further R&D as well as implementation experience would lead to additional insights concerning the techno-economic parameters of these processes. These experiences should be used to update the data used in this dissertation. Moreover, measure interdependencies could be considered in greater detail, by calculating the exact influence on costs and potentials instead of excluding measures in case interdependencies exist. Lastly, the need for cross-sectional measure implementation should be reduced by increasing the number of modeled processes and thereby enabling the possibility of identifying process-specific abatement measures.

Industry Model SmInd EU

The SmInd EU approach to industry modeling enables the scenario-based implementation of abatement pathways in the EU27+3. Future research could focus on increasing the number of processes and industrial abatement measures integrated in the model. Furthermore, additional industrial feedstock types could be included. The strict separation of calculations in MATLAB and the handling of input data and writing of results into the FREM database allow a flexible expansion of the database and calculation algorithms. Thereby SmInd EU algorithms could be expanded in several ways. Firstly, different measure implementation logics based on amortization periods or total costs could be implemented. Secondly, technology learning curves could be included to consider the effect of economies of scale on abatement measure cost. Thirdly, interconnections between processes such as steel and cement could be integrated dynamically, to reduce the parametrization effort. Furthermore, future research should focus on integrating industry and transport infrastructure modeling. Through this the transport infrastructure demand and position in the EU27+3 could be determined. This would have a significant impact on the abatement measure evaluation and provide a necessary step towards a holistic evaluation. Lastly, it is important to consider upstream as well as downstream emissions of industrial products. To do so, additional data as well as further parameters need to be included in SmInd EU.

The described regionalization approach differentiates between process and CST applications as well as energy and non-energy intensive industry branches. By using two different allocation keys the risk of misallocation is reduced, but not eliminated. Additional information about the share of employees active at administrative or production sites could enable a more detailed approach. In addition, the regionalization for energy-intensive industries could be improved by using final energy consumption shares instead of emission shares. This could be achieved by obtaining FEC data for the industry sites through thorough manual research. Regionalization via final energy consumption shares would enable the consideration of energy carriers in the allocation keys. The latter would benefit the analysis, since the currently used emission shares are based on direct emissions of industrial sites and therefore do not necessarily provide an accurate image of the electricity consumption at NUTS-3 level for all industry branches. In addition, the granularity of the regionalization approach could be increased by linking the transformation at process level to the respective industry sites. Ultimately the assumption that industry and employee locations are time and scenario independent can be alleviated to analyze the effects of employee and industry relocation on the European energy system. In particular, the position of possible future hydrogen or carbon transport infrastructure could pose incentives for industrial relocation. Possible benefits of increasing industrial symbiosis could also become influential location factors. Future research could therefore focus on deriving a multicriteria approach for determining time and scenario dependent allocation keys.

With respect to the load profile module further data is required to ensure the accurate modeling of synthetic load profiles for all EU27+3. Since the approach is based on real load data from Germany and Austria, input data from other countries is required to increase its accuracy. Another area of improvement would be to increase the granularity of load profiles used. Currently, synthetic industry branch profiles are used. Future research should focus on integrating process specific load profiles for the process modeled bottom-up and a generic profile for the remaining energy consumption. This way process specific details would be captured and the holistic approach to modeling maintained.

Integrated Scenario Process

In this dissertation the *From Word to Value* process was developed to improve the traceability and consistency of the quantification of qualitative scenario storylines. It was then applied to derive two holistic energy system scenarios hereby named quEU and solidEU. Further research should focus on applying the procedure to different models and subject areas to evaluate its validity and capability in supporting the construction of integrated scenarios. The application of the procedure showed that the degree of detail in the qualitative scenarios was insufficient for supporting the structured quantification of all industrial parameters. While the number of descriptors which can be used in CIB scenario construction is not limited mathematically, practical limitations do exist. Focusing storylines on a specific sector will therefore lead to loss of information at the other end. Further research should focus on determining a suitable degree of detail for the purpose of analyzing sectoral transformation pathways, and on developing methods which capture changes to the interrelationships between descriptors. A major drawback of current socio-technical scenarios is that these relationships are assumed constant over time. Sociopolitical dynamics are however subject to change, which can affect both qualitative and quantitative scenarios. Furthermore, it is the task of future research to identify the advantages and disadvantages of increased integration between qualitative and quantitative scenario creation with respect to industrial transformation pathway modeling.

Holistic Transformation Pathway and Measure Evaluation

The methods introduced in this dissertation increase the scope of CO_2 abatement measure evaluation by including system effects through dynamic abatement costs as well as additional evaluation criteria. Moreover, an exemplary transmission grid analysis was provided to demonstrate the importance of transport infrastructure evaluations. Despite these advancements, further steps could be undertaken to increase the scope of measure evaluation. First, the additional transport infrastructure demand for electricity, hydrogen and CO_2 required to enable transformation pathways such as solidEU should be analyzed. Second, the analysis should be expanded to include the entire industrial product life-cycle as well as all greenhouse gasses. Third, additional cost components such as labor and material cost are necessary to derive a full industrial cost balance and provide the basis for determining the effect of the industrial transformation on the global competitiveness of the European industry.

In summary, this thesis has proposed a number of strategies and methods to navigate the substantial changes needed to achieve European greenhouse gas emission targets over the next thirty years. It is the hope of the author that these methods will assist academia, policymakers and industrial practitioners to achieve informed decision-making and transformational pathways towards CO_2 abatement targets.

9 Appendix

9.1 Matching Eurostat Industry Branches and NACE Rev. 2 Groups

Industry branches	NACE Rev. 2 groups
Iron & steel	24.1 Manufacture of basic iron and steel and of ferro-alloys 24.2 Manufacture of tubes, pipes, hollow profiles and related fittings, of steel 24.3 Manufacture of other products of first processing of steel 24.51 Manufacture of structural metal products 24.52 Manufacture of tanks, reservoirs and containers of metal
Chemical & petrochemical	20 Manufacture of chemicals and chemical products 21 Manufacture of basic pharmaceutical products and pharmaceutical preparations
Non-ferrous metals	24.4 Manufacture of basic precious and other non-ferrous metals 24.53 Casting of light metals 24.54 Casting of other non-ferrous metals
Non-metallic minerals	23 Manufacture of other non-metallic mineral products
Transport equipment	29 Manufacture of motor vehicles, trailers and semi-trailers 30 Manufacture of other transport equipment
Machinery	25 Manufacture of fabricated metal products, except machinery and equipment 26 Manufacture of computer, electronic and optical products 27 Manufacture of electrical equipment 28 Manufacture of machinery and equipment
Mining & quarrying	07 (excl. 07.21) Mining of metal ores (excl. Mining of uranium and thorium ores) 08 (excl. 08.92) Other mining and quarrying (excl. Extraction of peat) 09.9 (Support activities for other mining and quarrying)
Food, beverages & tobacco	10 Manufacture of food products 11 Manufacture of beverages 12 Manufacture of tobacco products
Paper, pulp & printing	17 Manufacture of paper and paper products 18 Printing and reproduction of recorded media
Wood & wood products	16 Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
Construction	41 Construction of buildings 42 Civil engineering 43 Specialized construction activities
Textile & leather	13 Manufacture of textiles 14 Manufacture of wearing apparel 15 Manufacture of leather and related products
Non-specified	22 Manufacture of rubber and plastic products 31 Manufacture of furniture 32 Other manufacturing

Attachment 1: Matching Eurostat energy balance industry branches and NACE Rev. 2 groups[143]

[143] Own table based on [3]. NACE stands for „Nomenclature statistique des activités économiques dans la Communauté européenne".

9.2 Deep Dive - Calibrating Primary Steel and Steamcracking Final Consumption

[43] and [38] show that the most important primary steelworks components are the coke oven, sintering plant, blast furnace, blast oxygen furnace and blast (oxygen) furnace gas power plant. As stated in [26, 161] (for Germany) and [162] (for Europe), the energy input and consumption of these components is balanced in different sections of the Eurostat energy balance (i.e. *transformation input*, *transformation output*, *energy sector* and *final energy consumption*). Furthermore, some blast furnace inputs, such as *blast furnace gas*, are used both as reduction agents (non-energy use) and as energy carriers. It is the goal of the calibration process to ensure coherency with respect to the following aspects:

- A clear differentiation between energy and process related emissions, to avoid double-balancing of emissions
- Full accounting of energy consumption for bottom-up processes in SmInd EU and
- Exclusion of energy input used for the production of energy (e.g., heat, electricity), since this part of the energy supply-side.

To fulfill these requirements, the following steps are performed for primary steel production:

Differentiation between energy and process related emissions

According to [43], BFG is used in hot blast stoves to pre-heat air fed into the blast furnace. Simultaneously it is the predominant source of process emissions in primary steel production [26]. However, as stated in [162] and validated through own calculations for Germany, BFG used to pre-heat air in hot-blast stoves is balanced as FEC in [23].[144] In SmInd EU, BFG is consequently accounted for as FEC and not as feedstock gas resulting in process emissions. Process emissions for the primary steel production in this thesis consequently only include emissions from production and consumption of quicklime (based on [26] and [163]).[145]

Complete balancing of FEC and emissions for steel production[146]

According to [162], energy inputs used to pre-heat air in hot-blast stoves are balanced as FEC in [23]. This is covered by SmInd EU (see point above). Primary energy carriers such as coke oven coke, oil, lignite and hard coal are fully accounted for under *blast furnaces* in the transformation input section of [23]. To achieve full balancing of energy consumption for steel making in SmInd EU as well as coherency with the energy balance, the transformation input for blast furnaces is treated as FEC in the *iron & steel* industry. To avoid double balancing of emissions in the primary steel production, the specific process emissions are therefore reduced by the share accounted for by the transformation input, which is now treated as FEC.

Exclusion of energy input used for electricity production

With respect to the energy input for electricity production, only the waste gas energy carriers BFG and coke oven gas are relevant. Double balancing is avoided by ensuring that the bottom-up FEC for primary steel making does not encompass COG and BFG consumption listed in the *autoproducer electricity only* and *autoproducer CHP* rows of the transformation input section in the Eurostat energy balance [23]. For this, the primary steel making balancing area defined in [43] is adapted to exclude the blast furnace gas power plant.

The points listed above show that a variety of aspects are considered to ensure consistency between the bottom-up calculation of energy, feedstock demand and process emissions in European steel production.

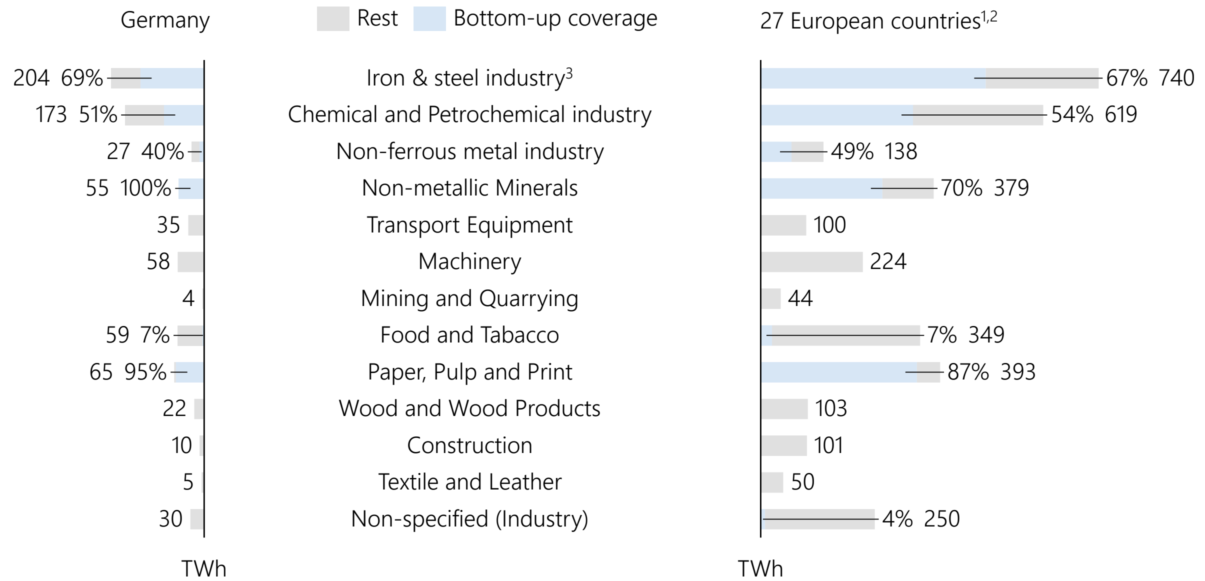
[144] Validation performed by comparing bottom-up BFG FEC- calculated using specific values from [43] and 2017 production tonnages [42, 59, 163] - to top-down BFG FEC in Eurostat. The result shows 94 % bottom-up coverage of BFG FEC for Germany.

[145] 0.07 tCO_2 / t_{CS} remain as process emissions. For Germany in 2017 ca. 15 Mt_{CO2} BFG emissions, which are categorized as process emissions by [26], are balanced energetically.

[146] Excluding energy carriers listed as imports in the Eurostat energy balance.

A similar procedure is performed for the energy and feedstock consumption of steamcrackers. The latter are used to produce high value chemicals (HVC) such as Ethylene, Propylene, Benzene, Toluol and Xylol [53]. Comparison and analysis of top-down and bottom-up energy and feedstock consumption (for Germany) shows that naphtha and LPG are fully accounted for as feedstock in [23].[147] The analysis in [23, 53, 54] show that FEC for high value chemical production is balanced as natural gas and heavy fuel oil. These energy carriers are by-products of the steamcracking process.[148]

9.3 Industrial Process Data



[1]Switzerland is part of non-specified due to lack of demand data at industry branch, application and energy carrier level.| [2]No bottom-up industry data of Malta and Cyprus included | [3]Includes transformation input in blast furnaces.

Attachment 2: Bottom-up coverage of industry branches in Germany and the EU, 2017

[147] Bottom-up calculation using production data derived from [47, 164, 165]. Specific consumption derived from [23, 26, 51, 53, 166].
[148] According to [53] hydrogen is also a by-product and used energetically. However, in [23] hydrogen is not balanced explicitly.

	Dairy	Paper	Chemical pulp	Mechanical pulp	Recycled paper	Steamcracker (Ethylene)	Steamcracker (Aromatics)	Methanol	Ammonia	Chlorine	Container Glass	Flat glass	Cement	Lime	Primary Steel	Secondary steel	H_2 Steel	Primary-aluminum	Secondary-aluminum
Austria	1120	4860	1269	325	1416	450	0	0	485	63	679	0	4880	416	7411	724	0	0	121
Belgium	1181	2022	271	229	1092	2016	602	5	1046	909	872	800	6491	1570	5395	2447	0	0	0
Bulgaria	230	384	236	0	0	0	0	0	381	0	292	143	2117	188	0	652	0	0	9
Croatia	341	349	0	39	0	0	18	0	456	0	58	0	2738	54	0	0	0	0	2
Cyprus	97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Czech Republic	892	908	452	8	1017	0	312	0	219	69	2294	1126	3948	849	4433	253	0	0	62
Denmark	692	147	0	5	590	0	0	0	0	0	82	0	0	62	0	0	0	0	31
Estonia	168	77	67	172	90	0	0	0	180	0	99	0	518	53	0	0	0	0	0
Finland	877	10277	7285	3396	640	360	90	0	0	63	0	0	1511	370	2702	1301	0	0	21
France	5156	8021	1613	0	7290	2797	840	14	1271	1160	2611	1300	16851	2393	10668	4838	0	416	181
Germany	7212	22925	1636	795	15270	5200	2712	1047	3133	4053	6573	2500	33991	6352	30827	12470	0.6	535	766
Greece	549	409	0	0	315	0	0	0	145	8	35	0	7786	129	0	1359	0	181	0
Hungary	655	807	0	0	559	0	645	0	413	406	105	52	2750	196	1603	298	0	0	40
Ireland	571	60	0	0	434	0	0	0	0	9	8	0	0	142	0	0	0	0	0
Italy	2916	9071	23	369	6479	1278	752	0	0	297	1471	900	19305	3600	4741	19327	0	0	743
Latvia	138	120	0	0	70	0	0	0	693	0	0	0	970	0	0	0	0	0	0
Lithuania	177	134	0	0	187	0	0	0	0	0	0	0	1023	27	0	0	0	0	0
Luxembourg	553	0	0	0	75	0	0	0	951	0	0	0	1058	0	0	2172	0	0	0
Malta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Netherlands	829	2983	0	37	2474	2668	1462	477	2797	717	276	0	2300	0	6781	0	0	36	124
Norway	567	1097	0	902	602	504	0	900	330	281	0	0	1694	219 [7)]	0 [7)]	603	0	1310	348
Poland	2507	4779	936	212	2750	0	561	0	2675	343	3737	1000	15807	1547	5703	4629	0	0	11
Portugal	849	2095	2648	0	640	364	254	0	0	120	292	143	3852	427 [7)]	0 [7)]	2100	0	0	18
Romania	567	529	0	0	607	0	46	0	616	175	209	103	8442	544	2329	1032	0	210	75
Slovakia	346	832	693	35	350	0	130	0	474	77	361	0	3782	584	4626	354	0	174	36
Slovenia	231	748	0	95	246	0	0	0	0	14	108	0	745	1060	0	673	0	84	18
Spain	4752	6218	1261	439	4560	1331	772	1	491	283	679	900	20360	1514	4835	9599	0	337	304
Sweden	1110	10260	8754	3398	1027	563	0	0	0	104	9	0	3015	829	3064	1628	0.1	123	73
Switzerland	785	1243	0	111	1279	0	0	0	168	40	0	0	4272	72	0	1500	0	0	150
UK	7557	3829	0	220	7770	2102	124	0	973	407	730	700	9359	1190	6001	1491	0	40	149
References:	1)	2)		3)		4)	5)	6)	7)	8)	9)	10)	11)	12)		13)		14)	15)

References: Derived values in color 1) [167]; production values used for Norway [168] as well as Luxembourg and the Netherlands [169] 2) Consolidated values from [59, 65, 164, 170]. 3) [170] 4) [164]; derived values based on 90 % utilization factor and 2017 steamcracker capacities [47] 5) [165] 6) [164], if 2017 is unavailable most recent historical was taken; for Germany [171]; for Norway [172] 7) [165]; derived values estimated based on plant capacities [48] and 2012 production figures [173] 8) [164]; derived values based on capacities from [50] 9) Derived based on total container glass production in Europe [174] and glass employee shares by country [175] 10) Derived values based on employee data [176] or flat glass production share by country and total flat glass production [177] 11) [59], most recent historical data used if 2017 was unavailable 12) [164], [178] 13) [42, 59, 163, 179] 14) [180], Norway derived from European total and sum of all other countries 15) [181]

Attachment 3: Production values in kt for SmInd EU processes, 2017

	Hard coal	Coke oven coke	Lignite	Peat	Other fossil fuels	Coke oven gas	Blast furnace gas	Oil	Natural gas	RES	Bio-mass	Non-RES waste	District heat	Sources and comments
Primary steel	0.29	0.56				0.02	0.11		0.02					[43, 84] balancing area adjusted to [23], H_2 balanced as feedstock
Secondary steel	0.37								0.63					
DRI steel	0.14								0.86					
Container glass								0.05	0.95					[32, 142]
Flat glass								0.09	0.90				0.01	
Primary aluminum					0.01			0.06	0.94					[142, 182]
Secondary aluminum								0.04	0.96					
Cement	0.08	0.04	0.21					0.01	0.01		0.18	0.47		[61, 142]
Lime	0.14	0.03	0.65						0.13			0.05		EU avg. except Germany [95, 115, 142]
Milk									1.00					[32, 142]
Ammonia									1.00					[51, 53]
Methanol								0.6	0.4					
Steamcracker									1.00					[23, 32, 51, 53, 54, 166]
Chlorine	0.05		0.01		0.10			0.02	0.53			0.09	0.20	[142]

Attachment 4: Energy carrier shares (process fuel consumption)[149]

[149] Note that most process substitution measures are electricity and hydrogen based and therefore not in this table. Paper and pulp have country specific shares.

Country	Hard coal	Lignite	Other fossil fuels	Oil	Natural gas	Biomass	Non-renewable waste	District heat
Austria & Belgium	0.04	0.03		0.02	0.45	0.46		
EU27 average: Bulgaria, Croatia, Denmark, Estonia, Greece, Hungary, Ireland, Latvia, Lithuania, Luxembourg, Norway, Romania, Slovenia, Switzerland	0.02	0.02	0.02	0.05	0.38	0.51		
Czech Republic	0.09	0.07		0.05	0.19	0.60		
Finland			0.06	0.05	0.14	0.74	0.01	
France	0.03	0.02	0.05	0.05	0.40	0.50		
Germany	0.05	0.04			0.49	0.22	0.06	0.14
Italy				0.05	0.95			
Netherlands					0.97	0.03		
Poland	0.13	0.12		0.04	0.03	0.68		
Portugal			0.01	0.10	0.15	0.74		
Slovakia	0.10	0.08			0.23	0.59		
Spain	0.01			0.05	0.62	0.32		
Sweden		0.01		0.09	0.01	0.89		
United Kingdom	0.03	0.03		0.01	0.88	0.05		

Attachment 5: Country specific energy carrier shares for paper and pulp[150]

	Hydrogen in kWh/t	LPG in kWh/t	Naphtha in kWh/t	Methanol in kWh/t	Source / Comment
Primary steel	135				13 TWh of European H2-demand for metal processing, heat treatment of steel and other processes [184] disaggregated to country level based on primary steel production tonnages
DRI steel	1,937				[43]
Ammonia	5,927				[46, 51–53, 166]
Olefines		3,010	9,031		
Aromatics		3,010	9,031		
Methanol	6,294				
MTO				15,478	
MTA				23,769	
E-Steamcracker			12,042		

Attachment 6: Specific feedstock demand for SmInd EU processes

[150] Confer [66, 183].

	Electricity in kWh/t	Fuel in kWh/t	Process emissions in tCO_2/t	Source / Comment	
Primary steel	See country specific values		0.07	[26, 162]	BFG accounted as energy-related.
Sec. steel	587	342	0.008	[42, 59, 163, 179]	
DRI steel	714	2,062	0.13		
Paper	530	1,529		[22, 32, 67]	Average of sulfite and sulfate process for chemical pulping.
Mech. pulp	2,057	-497			
Rec. paper	298	152			
Chem. pulp	639	3,611			
Cont. glass	389	1,621		[32, 33]	
Flat glass	917	3,028	0.2		
Primary Al	15,027	3,633	1.6	[33, 182]	
Secondary Al	150	892			
Cement	See country specific values		0.4	[33]	
Lime	109	1,139	0.7	[115]	EU avg. for all countries except GER
Dairy	139	444		[22, 32, 142]	Milk values taken for Dairy
SR Ammonia	2,067	1,833	1.17	[51, 53]	H_2-demand for NH_3 balanced as feedstock.
Methanol	167	3,306	0.97		
SC Olefines	621	9,972		[51–53, 166]	
SC Aromatics	278	1,944			
Chlorine	2,600	200		[51, 53]	
E-Cont. glass	830		0.043	[46]	
E-flat glass			0.178		
$P2NH_3$	2,914			[51, 53]	
P2MeOH	2,344		-1.373	[51, 53]	Includes direct air capture
MTO/MTA	1,389			[51, 53]	Includes P2MeOH process
E-steamcracker	1,306			[46]	
Innov. Prim. Al	14,610	3,532			

Attachment 7: Specific consumption and process emission values for SmInd EU processes

	Crude steel		Cement	
	Electricity in kWh / t_{CS}	Fuel in kWh / t_{CS}	Electricity in kWh / t	Fuel in kWh / t
Austria	147	3,805	724	113
Belgium	155	4,010	687	105
Croatia	173	4,451	857	123
Czech Republic	144	3,706	754	119
Finland	166	4,290	754	119
France	173	4,451	692	112
Germany	156	4,016	784	110
Greece	173	4,451	450	137
Hungary	141	3,641	754	119
Italy	173	4,451	578	116
Netherlands	156	4,034	617	230
Poland	156	4,020	956	127
Romania	143	3,683	754	119
Slovakia	153	3,950	754	119
Spain	159	4,107	913	110
Sweden	173	4,451	805	134
Switzerland	173	4,451	819	107
UK	172	4,447	909	132
Other EU27+3	173	4,451	754	119

Attachment 8: Primary steel and cement specific consumption values by country[151]

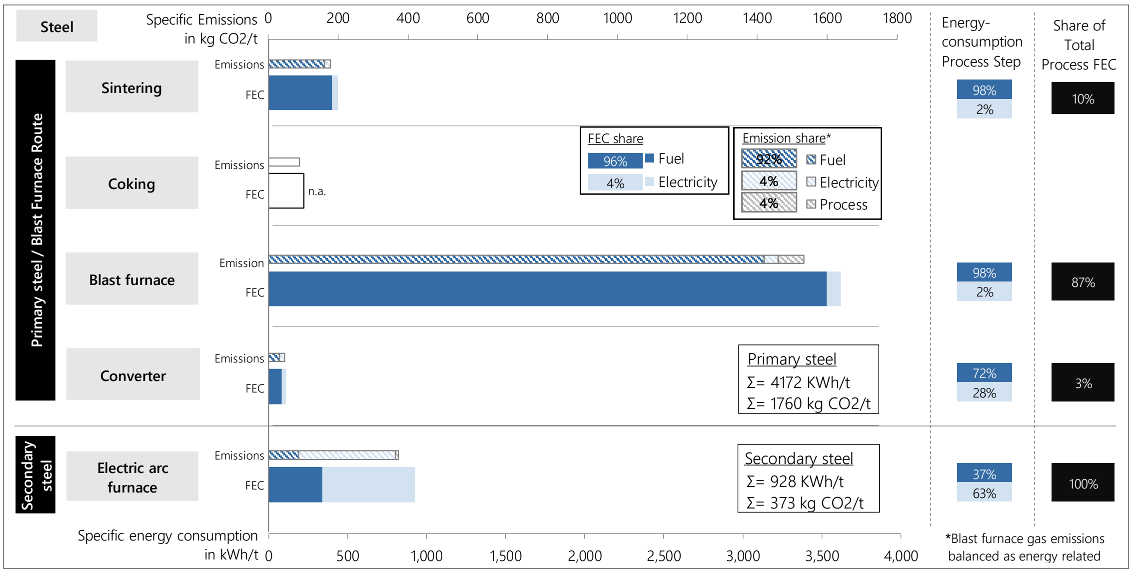
[151] Country specific scrap and pig iron share [42, 59, 163, 179]. Sintering plant, blast furnace, blast oxygen furnace included. Adjusted for clinker share [59].

9.4 Process Descriptions and Balances

This section of the appendix includes brief process descriptions including literature references for further and more detailed information. In addition, process-step-specific energy and emissions consumption are provided. The descriptions and sources are based on the Master's thesis [29], which was supervised by the author of this dissertation.

Crude Steel

Currently, iron and steel are produced mainly by two process routes. The primary route consists of a blast furnace and steel converter and is downstream of sinter production and the coke plant. Via the secondary route, steel scrap is recycled into steel products in the electric arc furnace. Attachment 9 shows the process steps for primary and secondary crude steel production as balanced in SmInd EU.



Attachment 9: Energy and emission balance by process-step for German steel production[152]

After sintering, during which fine iron ores are agglomerated to larger pieces of iron ore, and coking, where coking coal is turned into coke, the steel production via the blast furnace route consists of two main process steps [185, 186]:

1. Feeding the blast furnace with the input materials coke, iron ore, and aggregates such as lime. During this step the reduction agent carbon monoxide drifts upwards towards the sinking material charge, leading to the reduction of iron ore in the upper part of the blast furnace shaft. The gas then exits the blast furnace as blast furnace gas. Pig iron and slag are removed from the blast furnace at around 1,500 °C (slag is used as input for cement production). Maximum process temperatures lie at ~2,200 °C
2. In the basic oxygen furnace or converter, a further reduction of the carbon content of pig iron to less than two percent is achieved by blowing pure oxygen onto the iron ores using a water-cooled lance. The result is crude steel which is further processed in downstream processes such as casting, molding, and surface treatment

In the secondary steel production route crude steel is produced by melting steel scrap in an electric arc furnace [185, 186]. The process can be subdivided further into the following three steps:

1. Filling the electric arc furnace with steel scrap and further additives

[152] A scrap-share of 10 % is assumed. DRI production not included due to its currently low significance for emissions in steel production.

2. Melting steel scrap under temperatures of up to 3,500 °C. Steel melting takes place at approx. 1,800 °C
3. Acceleration of the process by blowing in oxygen or other gas mixtures

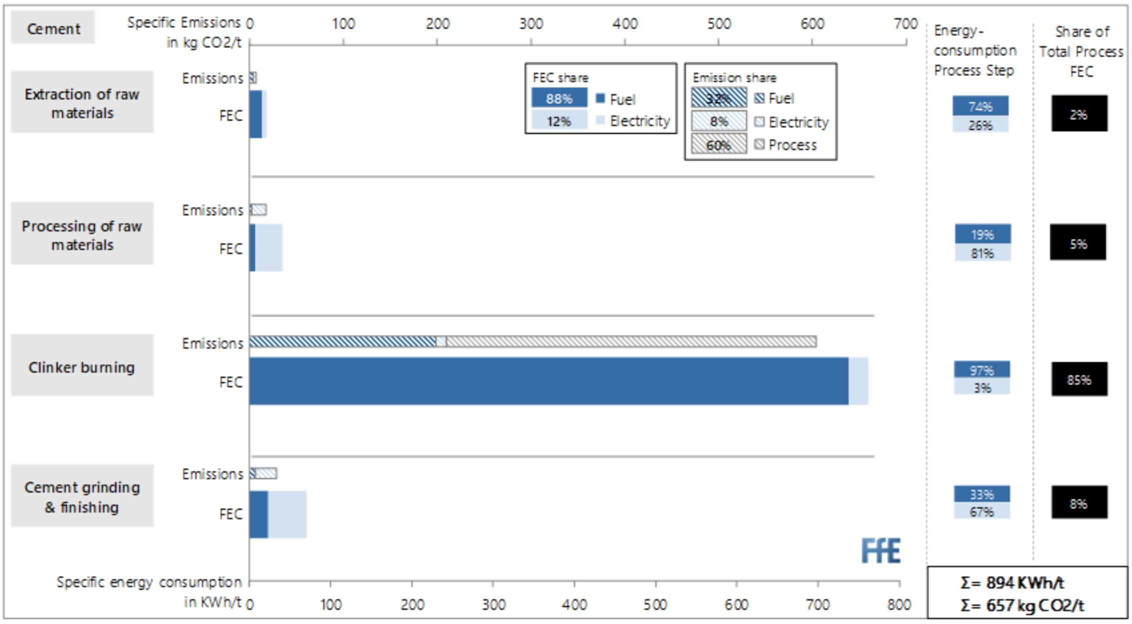
Once the desired steel composition has been achieved, the furnace is emptied. The majority of FEC is accounted for using electricity.

Cement

The cement production process consists of four main process steps [60, 185]:

1. Extraction of the main raw materials limestone, chalk or clay in mines using explosives
2. Crushing, homogenization (in mills) and drying of raw materials (mostly heat recovery from step three)
3. Burning of clinker in the calciner (~900°C) and rotary kiln at approximately 1,450 °C
4. Cement grinding in ball, vertical or material bed roller mills

Electrical FEC mainly results from grinding of raw materials and cement, while fuel consumption stems predominantly from the burning of clinker. The following figure shows the cement production steps and associated specific fuel, electricity consumption and emissions:



Attachment 10: Energy and emission balance by process-step for German cement production [153]

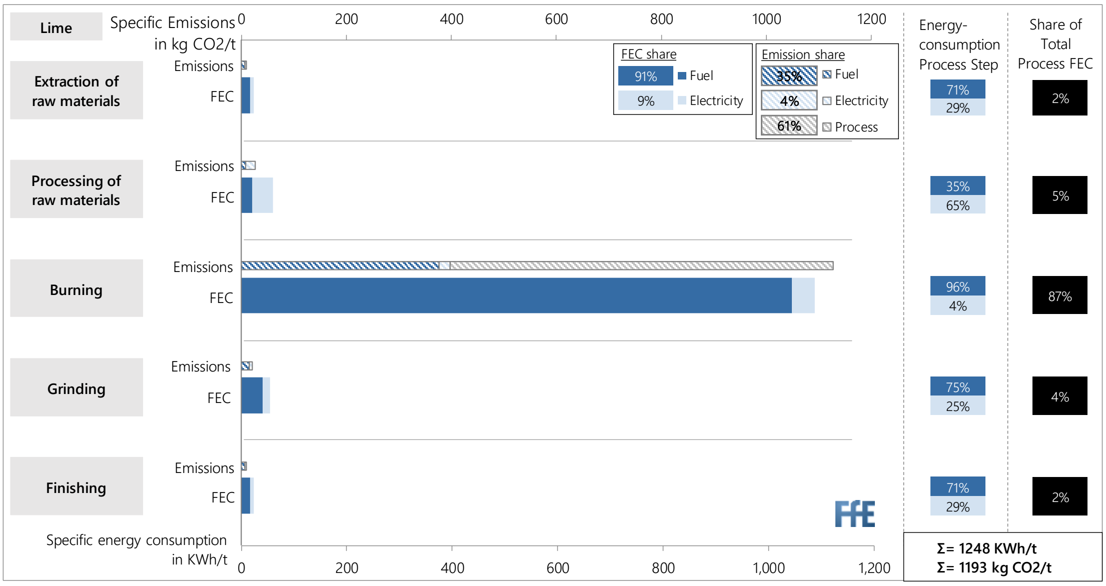
[153] Own illustration based on [19, 29]. A clinker-cement factor of 0.77 is assumed.

Lime

Lime production follows five main process steps [32, 38, 60]:

1. Raw material extraction
2. Crushing, grinding and, if necessary, washing of limestone and dolomite
3. Burning of the raw materials in shaft furnaces or rotary kilns at temperatures between 900 and 1,200 °C to produce quicklime. Lime is a direct input to primary steel production
4. Grinding of lime
5. Refining and finishing

Here, grinding is particularly electricity-intensive and burning (calcining) is a fuel-intensive process step. Limekilns are largely operated with lignite or natural gas. The following diagram shows further details:



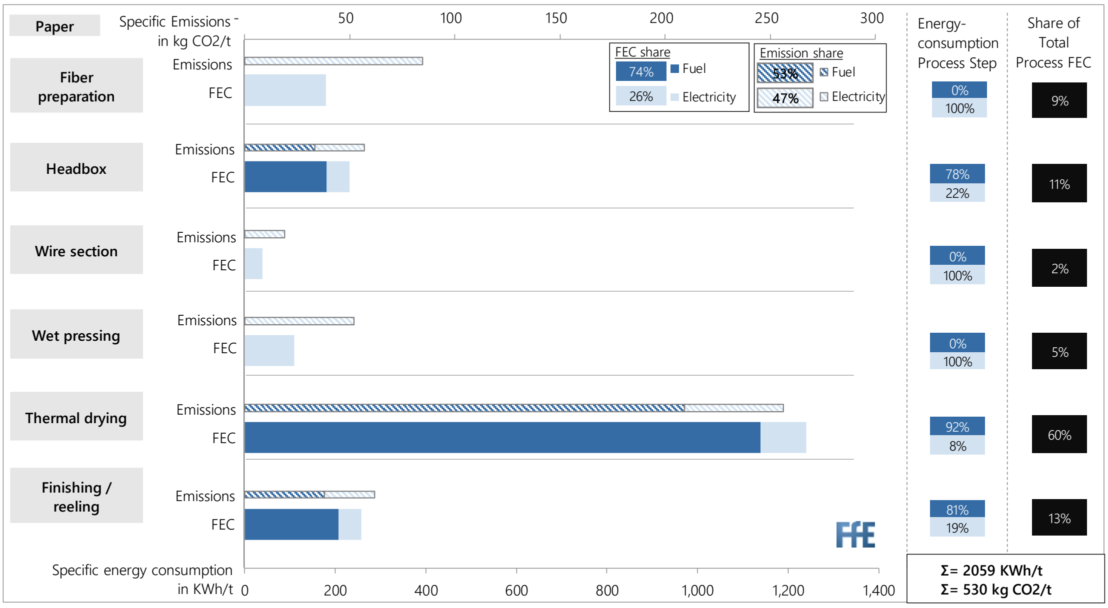
Attachment 11: Energy and emission balance by process-step for German lime production

Paper, Pulp and Recycled Paper

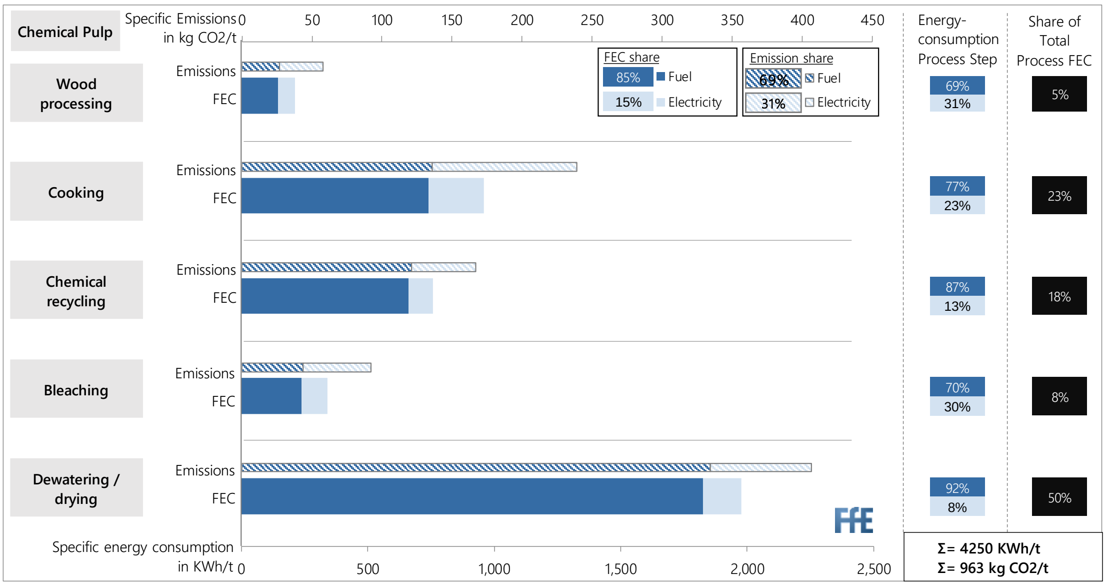
The paper production process consists of three main steps [67, 187]:

1. Production of primary (e.g., chemical and mechanical pulping) and secondary fibers (recycled paper)
2. Actual production of paper, cardboard and paperboard in the paper machine
    a. Stock preparation with the addition of water
    b. Headbox: Application of the fiber suspension into the inlet nip
    c. Wire section: sheet formation and dewatering to 80% water content
    d. Mechanical dewatering by pressing up to a moisture content of approx. 40-50 %
    e. Further dewatering of the paper web by adding heat
    f. Refining of the paper at a dry content of 90-98 %
3. Further paper processing such as surface treatment depending on the type of paper

The following figure shows the energy and emissions balance for the processes of chemical pulping, mechanical pulping, recycled paper and paper production in the paper machine.

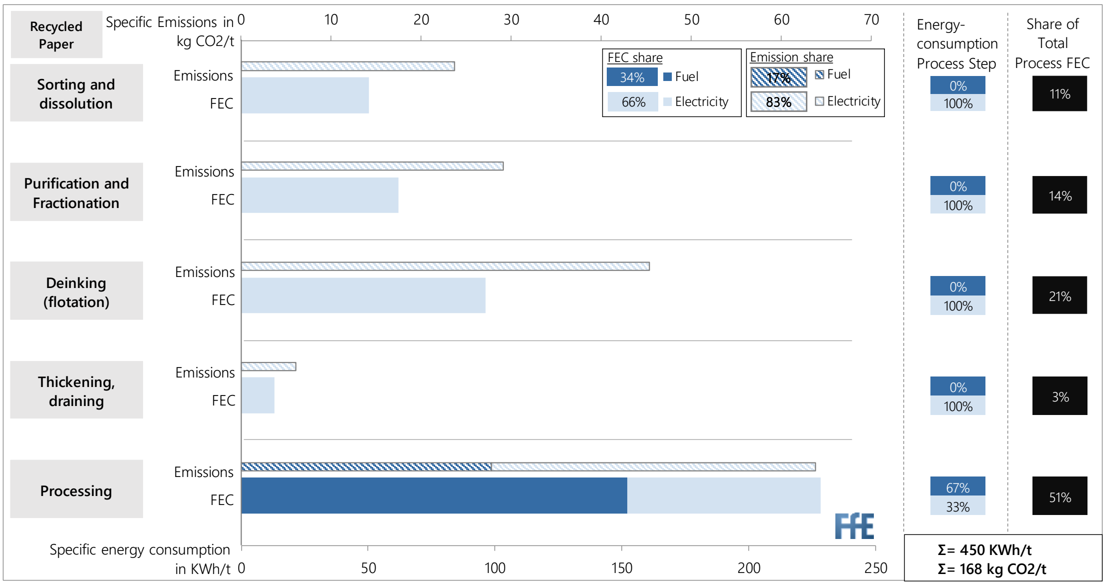


Attachment 12: Energy and emission balance by process-step for German paper production

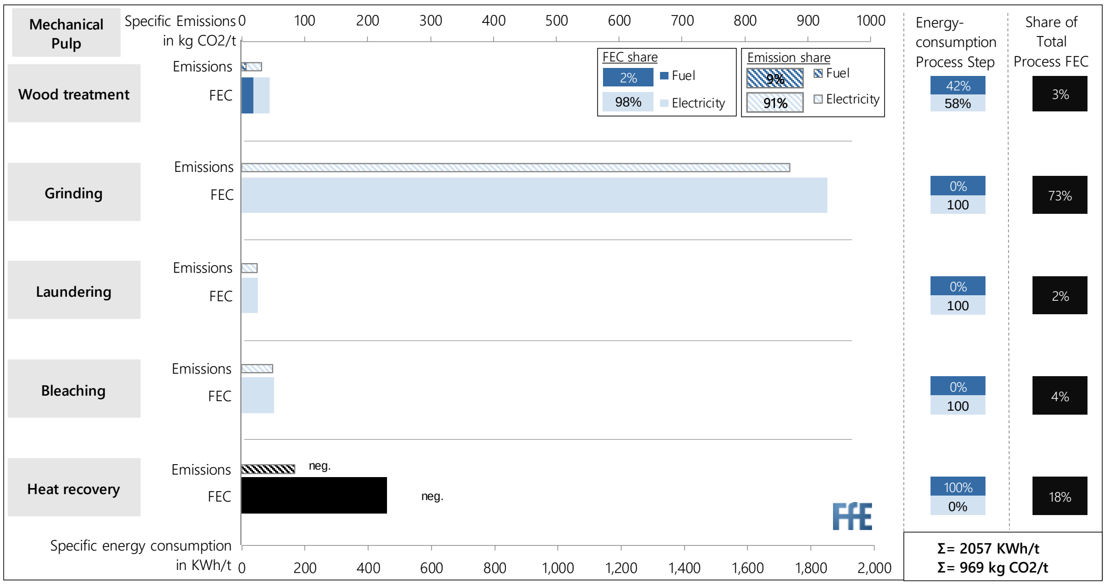


Attachment 13: Energy and emission balance by process-step for German chemical pulp production[154]

[154] Shows average of sulfite and sulfate process.



Attachment 14: Energy and emission balance by process-step for German recycling paper production



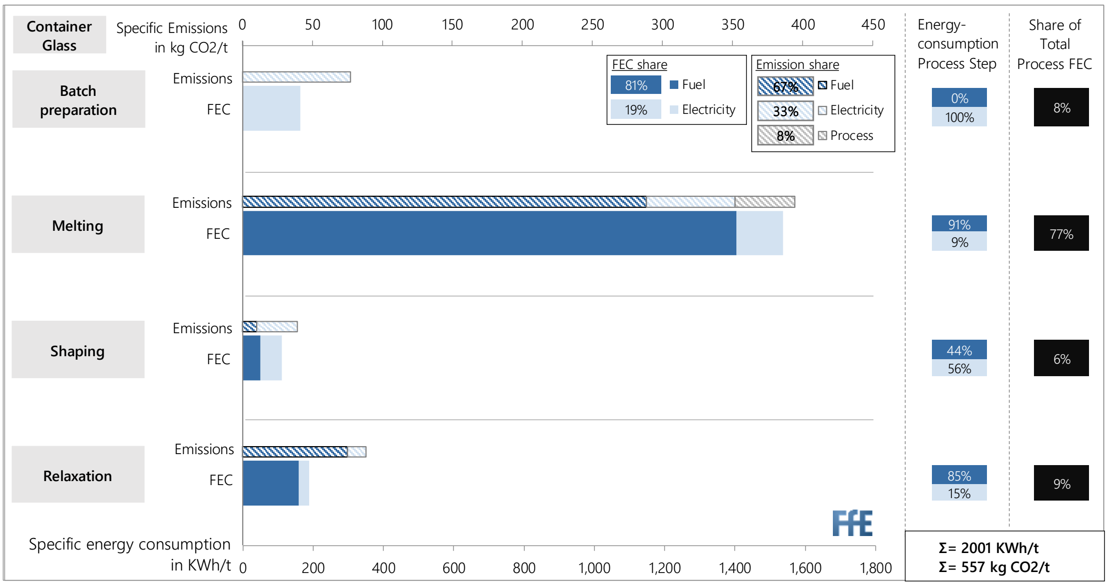
Attachment 15: Energy and emission balance by process-step for German wood pulp production

Container Glass

The container glass production consists of four main steps [29, 63]:

1. Homogenization of the raw materials
2. Melting the raw materials in the glass furnace at up to 1700°C
3. Extraction of the glass gobs from the feeder at 1,050 to 1,200° C and subsequent finishing in the forming machine
4. Relaxation or cooling and finishing of the glass products

Glass melting is the most energetic process-step. Fuels are mainly used for heat generation, in particular natural gas. Attachment 16 shows further process details.



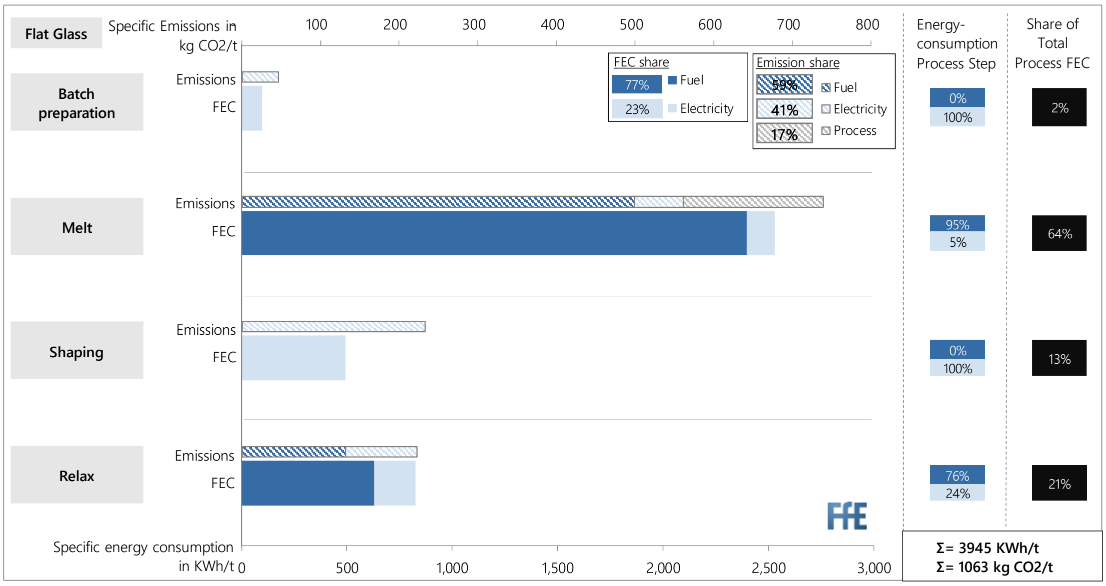
Attachment 16: Energy and emission balance by process-step for German container glass production

Flat Glass

The flat glass production consists of four main steps [32, 63]:

1. Batch preparation:
   a. Homogenization of raw materials (mainly quark sand and soda)
   b. Addition of lime, dolomite, and aluminum oxide as stabilizers, which give the glass its properties.
   c. Addition of recycled glass shards to further reduce the required melting energy
2. Melting of raw materials in a glass tank at temperatures up to 1,700°C. The glass is then drawn through a tin bath containing hydrogen and nitrogen under pressure
3. Cooling and shaping
4. Relaxation and refining

Glass melting is the most energetic process using mainly fuels, especially natural gas.



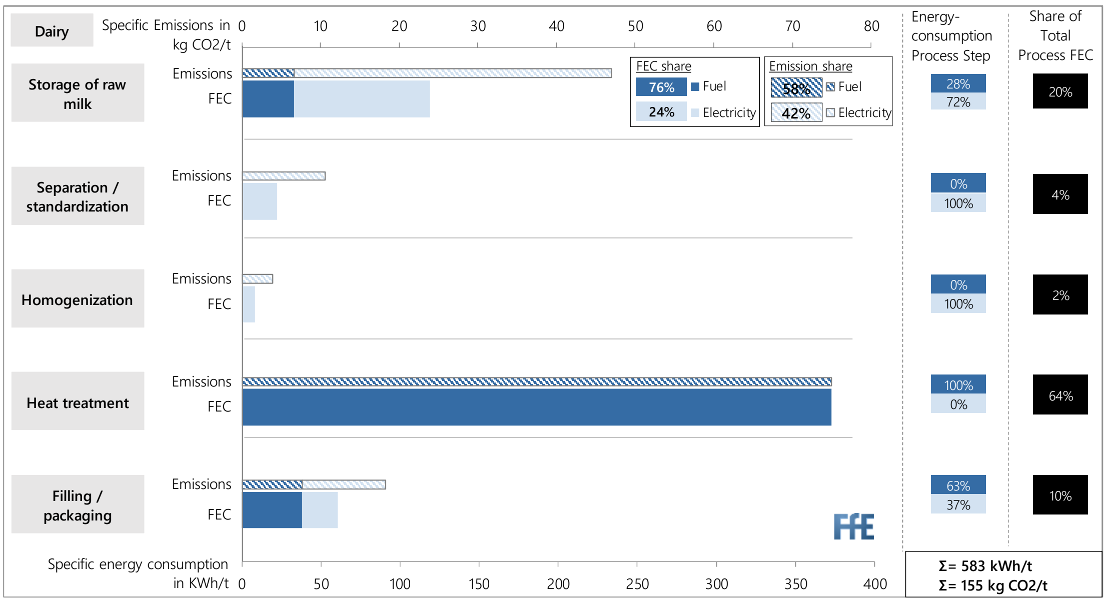
Attachment 17: Energy and emission balance by process-step for German flat glass production

Dairy Processing

The processing of consumer milk and fresh dairy products consists of 5 steps [32, 185]:

1. Storage of raw milk
2. Separation of milk into its components skim milk and cream and simultaneous purification process by means of a centrifuge
3. Homogenization to prevent or slow down creaming of the milk
4. Heat treatment to kill germs and preserve the milk. Different methods depending on the final product (e.g., UHT at 140 °C)
5. Filling and packaging

Electricity and fuels are primarily for heat generation. Natural gas is the main fuel used in this process. The following figure shows further process details.



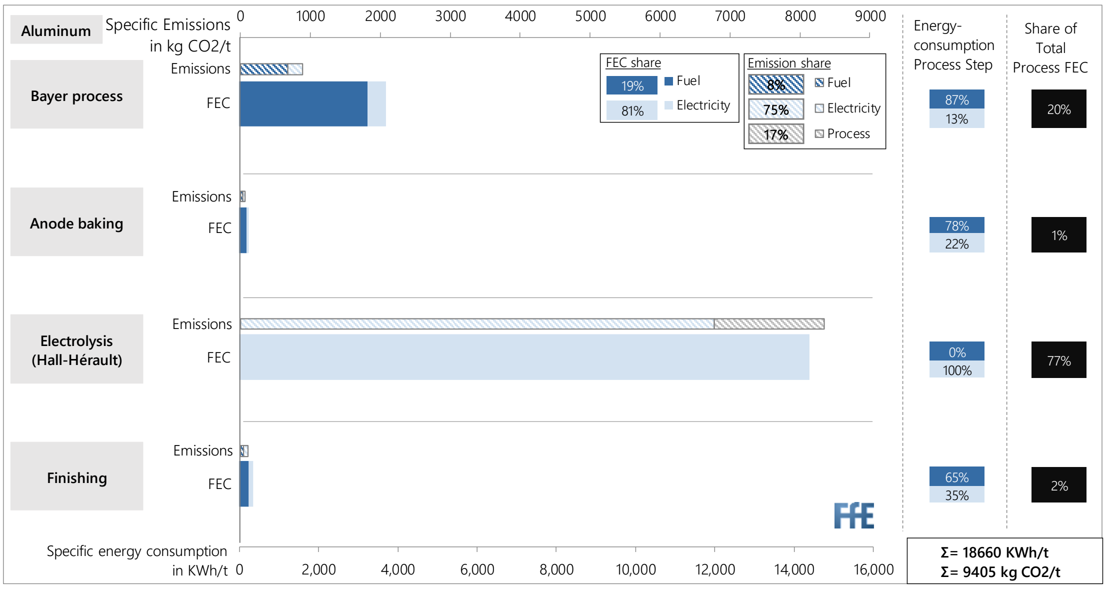
Attachment 18: Energy and emission balance by process-step for German container dairy production

Primary Aluminum

The production of primary aluminum can be divided into four main process steps [68]:

1. Production of alumina in refineries from bauxite, using the Bayer process at 1,200-1,300° C
2. Production of anodes made from a mixture of calcined petroleum coke, tar pitch, and the remains of unused anode ends
3. Production of primary aluminum by means of Hall-Héroult aluminum electrolysis. Reduction of the aluminum oxide at a temperature level of approx. 950-970 °C
4. Further processing such as casting

Electrolysis is the most energy and emission-intensive process step. Only electricity is used as an energy source. In the Bayer process, on the other hand, which accounts for around a quarter of total energy consumption, fuels are the main energy source used. The following figure shows further process details.



Attachment 19: Energy and emission balance by process-step for German primary Al production

Secondary Aluminum Production

Secondary aluminum is produced in a recycling process from aluminum. Secondary aluminum production consists of three process steps [68]:

1. Preparation of scrap: material separation of aluminum and contaminants such as paints and oils. Secondary aluminum energy consumption and emissions depend on the scrap purity
2. Melting of scrap at approximately 660 °C
3. Processing: casting of the liquid secondary aluminum into semi-finished products or cast alloys

The most energy-intensive steps here are melting and preparation. Due its low specific energy demand and low specific emissions, a detailed process overview is not provided.

Basic Chemicals

In the following, brief explanations of basic chemical production processes are provided. More detailed process descriptions can be obtained in [51, 53]. Due to the complexity of chemical production processes with diverse links between production process and heat recovery, the balancing of emissions and energy consumption was not performed on process step level for the chemical industry. Hence, detailed process diagrams are not included.

Ethylene, propylene and BTX (benzene, toluene, and xylene) are produced in five steps by the steam cracking process [32, 51, 53, 150]:

1. Preheating of raw material and mixing with process steam
2. Cracking at about 850°C, requiring superheated steam generated with natural gas or residue gases
3. Quenching
4. Compression and drying
5. Product cooling and separation: the condensate produced during the cooling processes contains several by-products, in particular various aromatics

Almost 100% of the energy requirement is covered by naphtha and LPG which enter the process as feedstock.
The production of **methanol** happens in two steps. First, synthesis gas is produced, then methanol [32, 51, 53, 150]:

1. Synthesis gas production by two different processes depending on the feedstock: steam reforming for natural gas (75% of methanol production) or partial oxidation for fuel oil and other hydrocarbons
2. Methanol synthesis: The main distinction is the pressure level. Methanol can be produced using a high-pressure, medium-pressure and low-pressure process (250 - 350 bar, 100 - 250 bar and 50 - 100 bar, respectively). Predominantly a metallic catalysts and temperatures between 220°C and 230°C are used

Energy requirements are covered almost exclusively by fuels.

Similar to methanol, the production of **ammonia** occurs in two steps. First, synthesis gas is produced and then ammonia is synthesized [32, 51, 53, 150]:

1. Synthesis gas production by two different processes depending on the feedstock: steam reforming for natural gas or partial oxidation for sludge and other hydrocarbons
2. Ammonia synthesis: by an exothermic reaction between nitrogen and hydrogen

Most of the energy demand is covered by fuels, especially natural gas.

Chlorine is produced by electrolysis of a sodium chloride solution. The main production processes are mercury (amalgam), diaphragm and membrane cell electrolysis [32, 51, 53, 150]:

- Mercury cell technology has been banned since the end of 2017 due to high FEC and mercury emissions
- Diaphragm technology is also being converted to asbestos-free membrane cell technology

Electrolysis accounts for the majority of total process energy consumption, which is mainly covered by electricity.

9.5 Industrial Abatement Measure Data

The following tables show the techno-economic data used to model abatement measures in the quEU and solidEU scenario. The technoeconomic data was previously published in [89] in German. All provided values are for Germany. Country specific differences exist for process substitution and cross-sectional-technology measures. A comprehensive list of the references used can be found in the German version of the measure list.

<table>
<tr><th>Measure</th><th>Process</th><th colspan="2">Implementation start year</th><th colspan="2">Lifetime</th><th colspan="2">Application factor</th><th colspan="2">Fuel Savings</th><th colspan="2">Electricity Savings</th><th colspan="2">specific CAPEX</th><th colspan="2">specific OPEX</th></tr>
<tr><td>*: measure is not implemented in the scenario</td><td></td><td colspan="2"></td><td colspan="2">[a]</td><td colspan="2">[%]</td><td colspan="2">[kWh/t]</td><td colspan="2">[kWh/t]</td><td colspan="2">[€/t]</td><td colspan="2">[€/t]</td></tr>
<tr><td></td><td></td><td>quEU</td><td>solidEU</td><td>quEU</td><td>solidEU</td><td>quEU</td><td>solidEU</td><td>quEU</td><td>solidEU</td><td>quEU</td><td>solidEU</td><td>quEU</td><td>solidEU</td><td>quEU</td><td>solidEU</td></tr>
<tr><td>Optimization of heat exchanger solution</td><td rowspan="6">Primary steel production</td><td>2030</td><td>2021</td><td colspan="2">30</td><td colspan="2">10</td><td colspan="2">36</td><td colspan="2">0</td><td colspan="2">4.2</td><td colspan="2">0</td></tr>
<tr><td>Top Gas Recycling (TGR)</td><td>2030</td><td>*</td><td>15</td><td>*</td><td>54</td><td>*</td><td>556</td><td>*</td><td>0</td><td>*</td><td>107</td><td>*</td><td>-8.5</td><td>*</td></tr>
<tr><td>Optimization of the sinter-pellet ratio</td><td>2030</td><td>2021</td><td>20</td><td>10</td><td colspan="2">100</td><td colspan="2">333</td><td colspan="2">0</td><td colspan="2">1</td><td colspan="2">0</td></tr>
<tr><td>Injection of hydrogen-rich reducing agents</td><td>2030</td><td>2021</td><td>20</td><td>10</td><td colspan="2">100</td><td colspan="2">164</td><td colspan="2">19</td><td colspan="2">38</td><td colspan="2">0</td></tr>
<tr><td>Converter gas recycling</td><td>2030</td><td>2021</td><td colspan="2">10</td><td colspan="2">40</td><td colspan="2">139</td><td colspan="2">0</td><td colspan="2">38</td><td colspan="2">0</td></tr>
<tr><td>Electricity generation from waste heat</td><td>2030</td><td>2021</td><td colspan="2">15</td><td colspan="2">30</td><td colspan="2">0</td><td colspan="2">22</td><td colspan="2">5.2</td><td colspan="2">0</td></tr>
<tr><td>Conversion or upgrading of ladle heaters</td><td rowspan="3">Secondary steel production</td><td>*</td><td>2021</td><td>*</td><td>20</td><td>*</td><td>50</td><td>*</td><td>1.21</td><td>*</td><td>-0.24</td><td>*</td><td>0.38</td><td>*</td><td>0</td></tr>
<tr><td>Scrap preheating</td><td>2030</td><td>2021</td><td colspan="2">10</td><td colspan="2">100</td><td colspan="2">0</td><td colspan="2">81</td><td colspan="2">166.7</td><td colspan="2">0</td></tr>
<tr><td>Process optimization</td><td>2030</td><td>2021</td><td colspan="2">20</td><td colspan="2">80</td><td colspan="2">0</td><td colspan="2">46</td><td colspan="2">1.7</td><td colspan="2">0</td></tr>
</table>

Attachment 20: Technical parameters of process efficiency measures in iron & steel industry[155]

[155] See the list of references for each measure in the previously published German version [89].

Measure	Process	Implementation start year		Lifetime		Application factor		Fuel Savings		Electricity Savings		specific CAPEX		specific OPEX	
				[a]		[%]		[kWh/t]		[kWh/t]		[€/t]		[€/t]	
		quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU
Magnetic compensation	Primary aluminum production	2030	2025	10	10	100		0		1070		0		0	
Optimized process control	Primary aluminum production	2030	2025	10	10	37.1		0		713		7		0	
Heat recovery (ORC) (electrolysis)	Primary aluminum production	2030	2025	15	15	100		0		713		5.8		0	
Heat recovery (ORC) (anode jaws)	Primary aluminum production	2030	2025	15		100		0		713		5.8		0	

Attachment 21: Technical parameters of process efficiency measures in non-ferrous metals industry[155]

Measure	Process	Implementation start year		Lifetime		Application factor		Fuel Savings		Electricity Savings		specific CAPEX		specific OPEX	
**: No data. Cost calculation via dummy efficiency measures				[a]		[%]		[kWh/t]		[kWh/t]		[€/t]		[€/t]	
		quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU
Indirect heat recovery	Milk processing	2030	2025	20		10		7		0		**		**	
Partial homogenization	Milk processing	2030	2025	20		30		0		4		**		**	
Energy efficient homogenization	Milk processing	2030	2025	20		20		0		2		**		**	
Ultra high temperature (UHT) heating	Milk processing	2030	2025	20		90[156]		11		8		**		**	
Optimized cleaning	Milk processing	2030	2025	20		70		11		0		**		**	

Attachment 22: Technical parameters of process efficiency measures in food & tobacco industry[155]

[156] Luxembourg: 10%

Measure	Process	Implementation start year		Lifetime		Application factor		Fuel Savings		Electricity Savings		specific CAPEX		specific OPEX	
*: measure is not implemented in the scenario				[a]		[%]		[kWh/t]		[kWh/t]		[€/t]		[€/t]	
		quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU
General measures	Ammonia	2030	*	20	*	20	*	592	*	25	*	6	*	0	*
Minor improvements of the reformer	Ammonia	2030	*	20	*	20		373	*	16	*	5	*	0	*
Major improvements of the reformer	Ammonia	2030	*	20	*	10	*	1067	*	44	*	24	*	0	*
Improvement of synthesis	Ammonia	2030	2025	20		25		267		11		7		0	
Improved CO_2 capture	Ammonia	2030	*	15	*	30	*	240	*	10	*	4	*	0	*
General measures	Ethylene	2030	2021	10		20		100		0		4		0	
Steamcracker improvement	Ethylene	2025	2021	25		40		1042		0		8		0	
Advanced distillation columns	Ethylene	2030	2021	15		20		111		0		3		0	
General measures	Methanol	2030	2021	20		20		598		19		5		0	
Minor improvements of the reformer	Methanol	2030	2021	20		20		377		12		5		0	
Major improvements of the reformer	Methanol	2030	2021	20		10		1078		33		24		0	
Improved CO_2 capture	Methanol	2030	2021	15		30		242.5		7.5		6		0	
Change from amalgam process to membrane process	Chlorine	2030	2025	30		0		0		1000		800		0	
Heat recovery	Chlorine	2030	2021	30		20		8		25		0.1		0	
Better process control	Chlorine	2030	2021	30		20		23		74		1.4		0	
Membrane electrolysis based on oxygen depolarized cathode	Chlorine	2035		30		25		140		685		1		0	
Change from diaphragm process to membrane process	Chlorine	2030	2025	30		0[157]		37		47		800		0	
Improved membrane process	Chlorine	2030	2021	30		100[158]		31		150		0.3		0	

Attachment 23: Technical parameters of process efficiency measures for basic chemicals[155]

[157] Germany: 21%, France: 13%
[158] Germany: 79%, France: 87%

Measure	Process	Implementation start year		Lifetime [a]		Application factor [%]		Fuel Savings [kWh/t]		Electricity Savings [kWh/t]		Specific CAPEX [€/t]		Specific OPEX [€/t]	
*: measure is not implemented in the scenario		quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU
Batch and shard preheating	Container glass production	2030	2021	12		40		112		45		20.4		0	
Increase in shard use		2030	2021	20		90		56		0		0		0	
Waste heat utilization for power generation		2030	2021	15		100		0		28		12.6		0	
Substitution of raw materials		2030	2021	20		20		24		0		0		3.5	
Optimized burner design (oxy-fuel)		2030	*	12	*	90	*	270	*	-29	*	106	*	0	*
Replacement of ball mills	Cement production	2030	2025	20		58		0		8		9.8		0	
Replacement transport systems		2030	2025	20		57		0		2		8.7		0	
Homogenization by gravity		2025		25		62		0		2		3		0	
Heat Recovery		2030	2025	20		42		0		6		31		0	
Optimized process control		2030	2025	10		20		24		2		1.6		0	
Retrofit precalciners		2030	2025	40	25	65		89		0		22.6		0	
Replacement of Lepol furnaces		2030	2025	40	25	2		186		4		85		0	
Replacement rotary/satellite cooler		2030	2025	20		16		49		-2		8.8		0	
Modernization of grate coolers		2030	2025	20		16		5		0		0.8		0	
Retrofit of cyclones		2030	2025	20		57		0		2		3.7		0	
Replacement of ball mills		2030	2025	20		56		0		26		15.3		0	
Retrofit high efficiency separators		2030	2025	20		61		0		4		1.8		0	
Decreasing slag use		*	2030	*	20	*	100	*	-279	*	0	*	0	*	0
Higher efficiency furnace design	Lime production	2030	2025	30	25	75		221		0		33.7		0	
Replacement of existing mills		2030	2025	20		89		0		13		8		0	
Batch and shard preheating	Flat glass production	2030	2021	12		100		112		15		20.4		0	
Increase in shard use		2030	2021	20		100		0		3		0		0	
Waste heat utilization for power generation		2030	2021	15		100		0		84		12.6		0	
Substitution of raw materials		2030	2021	20		50		0		75		0		0	
Optimized burner design (oxy-fuel)		2030	*	12	*	100	*	280	*	-29	*	106	*	0	*

Attachment 24: Technical parameters of process efficiency measures in non-metallic minerals industry[155]

Measure	Process	Implementation start year		Lifetime		Application factor		Fuel Savings		Electricity Savings		specific CAPEX		specific OPEX	
				[a]		[%]		[kWh/t]		[kWh/t]		[€/t]		[€/t]	
		quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU	quEU	solidEU
Black liquor gasification	Chemical pulp production	2030	2025	20		100		0		478		432		0	
High consistency pulp dissolution	Waste paper production	2030	2025	10		70		0		7		3.3		0	
Efficient sieving		2030	2025	10		80		0		12		6.2		0	
Heat recovery bleaching		2030	2025	20		80		8		0		0.9		0	
Optimization of the deinking process		2030	2025	10		100		0		14		4		0.1	
Efficient disperser		2030	2025	15		70		0		6		1.4		0	
Higher efficiency refiners	Mechanical pulp production	2030	2025	10		95		0		33		7.2		0	
Optimization refiner	Paper machine	2030	2025	5		70		0		20.8		6.2		0	
Chemical fiber modification		2030	2025	20		100		51		45.6		4.6		3.4	
Steam blow box		2030	2025	15		36		50		0		4.5		0	
Use of shoe presses		2030	2025	20		43		152		0		32.5		0	
New drying processes		2040	2025	10		100		183		0		96.7		0	
Heat recovery - waste heat utilization		2030	2025	20		50		298		0		1.1		0	

Attachment 25: Technical parameters of process efficiency measures in paper, pulp & print industry[155]

Measure	Energy application	Implementation start year	Lifetime	Application factor	Fuel Savings	Electricity Savings	specific CAPEX	specific OPEX
			[a]	[%]	[MWh/plant]	[MWh/plant]	[thous. €/plant]	[thous. €/plant]
Electric boiler	Process heating (100-240°C)	2025	20	100	9213	-8937	157	0
Heat pump	Process heating (<100°C)	2025	20	100	7928	-2197	124	0
	Space heating & warm water	2025	20	100	878	-243	22	0

Attachment 26: Technical parameters of cross-sectional electrification measures for Germany[155]

Measure	Implementation start year	Lifetime	Application factor	Fuel Savings*	Electricity Savings*	Specific CAPEX	Specific OPEX
*: Country specific values. Values shown are for Germany		[a]	[%]	[MWh/plant]	[MWh/plant]	[thous. €/plant]	[thous. €/plant]
Replacing other high-intensity discharge lamps with LEDs	2021	10	16	0	166	7.4	0
Replacing fluorescent tubes with LEDs	2021	10	58	0	145	105.1	0
Lighting - control optimization	2021	15	70	0	117	18.6	0
Increased efficiency of fossil fuel heat generators	2021	25	54	465	0	72.4	0
Insulation of heat distribution	2021	20	22	1090	0	5.5	0
Heat recovery cooling	2021	15	33	321	0	24.5	0
Heat recovery low temperature heat generation	2021	20	57	1833	0	94.7	0
Heat recovery ventilation	2021	25	27	1948	0	50.3	0
Lowering the pressure level	2021	15	53	0	32	0.4	0
Efficient air compressors	2021	15	41	0	136	17.2	0
Elimination of compressed air leakage	2021	1	99	0	21	2.6	0
Compressed air control optimization	2021	10	48	0	95	3	0
Heat recovery compressed air	2021	15	36	177	0	16.9	0
High-efficiency drives	2021	15	49	0	477	16.4	0
Efficient power transmission	2021	5	19	0	130	0.5	0
Control-technical optimization electric drives	2021	15	24	0	734	10.9	0
Efficient IT devices	2021	5	38	0	41	10.2	0
Server virtualization	2021	1	71	0	148	4.5	0
Efficient cooling unit	2021	15	54	0	211	28.4	0
Optimized cooling distribution	2021	15	73	0	257	2.3	0
Complete renewal of the ventilation system	2021	25	28	0	376	37.5	0
Ventilation - efficient drives	2021	15	52	0	123	1.9	0
Ventilation - efficient power transmission	2021	5	57	0	38	0.3	0
Ventilation optimization	2021	25	43	0	205	3.1	0

Attachment 27: Technical parameters of cross-sectional efficiency measures for Germany[155]

Process	Reference	Measure	Implementation start year	Lifetime	Application factor	Specific CAPEX	Specific OPEX
				[a]	[%]	[€/t]	[€/t]
Steel production	Blast furnace	Electric Arc Furnace (EAF)	2025	20	*	106	75
Primary steel production		Direct reduction H2 + EAF (DRI-EAF)	2025	20	*	1856	62
Primary aluminum production	Aluminum electrolysis	Aluminum electrolysis with innovative electrodes	2035	10	100	-574	46.33
Container glass production	Melting Furnace	Electric melting furnace	2025	20	100	676	0
Flat glass production			2025	15	100	457	0
Ammonia production	Steam reforming + Ammonia synthesis	Hydrogen + Air separation unit	2025	25	100	-131	0
Methanol production	Steam reforming + Methanol synthesis	Methanol via Hydrogen + CO_2	2025	25	100	190	0
Olefin production	Steamcracker (Olefin)	Power to Methanol to Olefins	2025	25	60	423.7	0
		Electrocracker	2040	10	40	250	37.5
Aromatics production	Steamcracker (Aromatics)	Power to Methanol to Aromatics	2025	25	60	817	0
		Electrocracker	2040	10	40	250	37.5

*: Country specific values because of scrap availability

Attachment 28: Technical parameters of process route change measures[155,159]

	Application factor [%]												
	Austria	Belgium	Czechia	Finland	France	Germany	Hungary	Poland	Romania	Slovakia	Sweden	United Kingdom	Other EU countries
EAF	10	45	6	48	45	10	19	81	44	8	53	25	0
DRI-EAF	90	55	94	52	55	90	81	19	56	92	47	75	100

Attachment 29: Application factor of innovative processes in iron & steel industry[155]

[159] Specific CAPEX and OPEX are provided as difference compared to the reference technology.

9.6 Radar for the Holistic Evaluation of Industrial Abatement Measures[160]

	Criteria	Criteria scores			Show-stopper?	Mentions	Literature (selection)
	Sociopolitical						
1	Occupational health	Sinks	No consequences	Increases	Yes	18	[154, 188]
2	Job effect	Sinks	No consequences	Increases		21	[189]
3	Sociopolitical acceptance	Rejected	Partly Rejected	Not Rejected		23	[153, 154, 188]
4	Contribution to regional development	Negative	Not influenced	Positive		14	[190]
5	Further societal development	Open question				30	
	Ecological						
6	Greenhouse gas reduction potential	Potential < 1%	1%≤ Potential <95%	Potential ≥ 95%	Yes	47	[154]
7	Water quality	Sinks	No consequences	Increases	Yes	31	[190]
8	Soil quality	Sinks	No consequences	Increases	Yes	21	
9	Resource demand	Increases	Not influenced	Sinks		34	
10	Recycling quota	Sinks	Not influenced	Increases		14	
11	Further ecological criteria	Open question				33	
	Economic						
12	Investment barrier	High, despite incentives	Incentives necessary	No barrier		46	Based on [191]
13	Payback period (PP)	PP > 3 years	3 years ≥ PP> 1 year	PP ≤ 1 year		43	[192]
14	Internal rate of return (IRR)	IRR < 10%	10% ≤ IRR < 30%	IRR ≥ 30%			
15	Economic potential	Sinks	No consequences	Increases		13	[193]
	Regulatory						
16	Compatibility with current law	Not given	Grey area	Yes		8	[194]
17	Compliance with regional environmental standards	Not given	Yes		Yes	9	[154]
	Technological						
18	Energy system effects	Negative	No influence	Positive		3	Based on [6, 195]
19	Technology readiness level	1,2,3,4	5,6,7,8	9	Yes	19	[152]
20	Natural replacement cycles until 2050	Zero	1 - 2	Min. 3		11	
21	Production security	Sinks	No consequences	Increases	Yes	16	
22	Complexity of technical transition	Increases	No consequences	Sinks		17	[188]
23	Complexity of technical application	Increases	No consequences	Sinks		7	
24	Product quality	Sinks	No consequences	Increases	Yes	11	Based on [188, 196]

[160] See [151] for the full list of references. Evaluation of number of mentions are based on 66 references.

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