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The *Industriewende*: Developing Scenarios for a Carbon-Neutral Industry in Germany

by

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Abstract

Scenario planning provides stakeholders with a tool to understand the future. Through the depiction of different possible futures, it informs decision-making and challenges how we think about future developments. In Germany, a series of studies modeled various pathways to climate neutrality by 2045/50. Although giving valuable insights, they fall short of explaining how they arrived at the scenarios they modeled.

This thesis aims to address this gap. It focuses on the decarbonization of the industry, which is one of the key challenges on the path to achieve climate neutrality by 2045, as targeted by the German government. It does so by applying a systems approach, which aims to explain other developments that are linked to industry as well. In addition to techno-economic factors, qualitative developments such as societal trends, corporate strategies, the political framework, and others are also taken into account. To achieve this, the thesis utilizes a cross-impact balancing (CIB) technique. CIB allows for the construction of consistent scenarios by creating a matrix of interactions between different developments. Through a structured expert elicitation, these interactions are assessed one by one on whether they promote or restrict each other. For the expert elicitation, essays portray the possible course that each of the individual developments considered could take. Then, the matrix is analyzed with software. That way, sixteen scenarios are developed, which are consistent within the CIB framework. Four of these are described in more detail through storylines: one scenario where developments occur late and decarbonization seems at risk, one where PtX is the dominant energy carrier, one where a quick scale-up of technologies makes decarbonization possible, and one where societal change and the establishment of a circular economy leads to a reduction in demand. Furthermore, the impact of the different developments upon each other is assessed.

Because of how the method is constructed, a few uncertainties regarding the scenarios arise, e.g., about the combination of some developments in the scenarios. Still, the structured approach offers advantages over the usual, less systematic scenario planning techniques.

Preface

Over the last six months, I have had the pleasure to write my master's thesis at the Energy System Analysis department of the Fraunhofer ISE in Freiburg. It has been a valuable and educative experience, in which I learned from both my colleagues and supervisors. The product of this time lies in front of you.

While I am proud to hand in this thesis with my name on the title page, several people added their guidance, support and review, for which I am very thankful. I am grateful for Charlotte Senkpiel's guidance, without which this process would have been impossible, as well as her critical comments, that significantly improved the thesis. I am equally grateful for Wolfgang Eichhammer's supervision. He provided constructive discussions and valuable observations from an expert's perspective.

Furthermore, I was blessed with support and review from Nyasha Grecu and would like to thank Sylvie Ramakers and everyone else who gave helpful comments and feedback. Lastly, I would like to thank Markus Kaiser and the entire IND-E team, who provided input, supported and discussed descriptors, states, and essays with me, as well as everyone who participated in the workshops.

With this thesis, after two and a half years, my study of Energy Science at Utrecht University comes to an end. Still much too short, I have thoroughly enjoyed it – from the beginning to the end.

Nikolaus Kelnreiter,

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List of Abbreviations

BAU	Business-as-usual
BECCS	Bio-energy with carbon capture and storage
CBAM	Carbon Border Adjustment Mechanism
CCfD	Carbon Contract for Difference
CCS	Carbon capture and storage
CI	Cross-impact
CIA	Cross-impact analysis
CIB	Cross-impact balance
CIM	Cross-impact matrix
CO_2	Carbon dioxide
DACCS	Direct air carbon capture and storage
dena	German Energy Agency, *Deutsche Energie-Agentur GmbH*
EU	European Union
ETS	Emission Trading System
EWI	Institute of Energy Economics at the University of Cologne, *Energiewirtschaftliches Institut an der Universität zu Köln*
GHG	Greenhouse gas
GW	Gigawatt
HTHP	High temperature heat pump
H2-DRI	Hydrogen direct reduction iron making
IL	Intuitive Logics
INATECH	Department of Sustainable Systems Engineering, University of Freiburg
IND-E	Decarbonization and Electrification Potentials in the German Industry, *Dekarbonisierungs- und Elektrifizierungspotentiale in der deutschen Industrie*
IPCC	Intergovernmental Panel on Climate Change
ISE	Institute for Solar Energy Systems
ISI	Institute for Systems and Innovation Research

KSG	Climate protection law, *Klimaschutzgesetz*
LNG	Liquefied natural gas
LULUCF	Land use, land-use change and forestry
MTA	Methanol-to-aromatics
MTO	Methanol-to-olefins
Mt-CO_2-eq.	Megatons of carbon dioxide equivalent
MWh	Megawatt hour
NEP	German grid development plan, *Netzentwicklungsplan*
PtH	Power-to-heat
PtX	Power-to-X
PV	Photovoltaic
SME	Small and medium-sized enterprise
T.	The technique
TRL	Technological readiness level

1. Introduction

1.1. Motivation

The climate crisis is arguably one of the greatest challenges humanity has ever faced [1]. To keep its consequences as manageable as possible, in the Paris Agreement, 196 signatory countries agreed to limit global warming to "well below 2 °C" and "preferably 1.5 °C" [2]. However, current national climate pledges combined fall short of reaching even the 2 °C target, let alone the 1.5 °C target [3]. The latter also holds true for the European Union (EU) and, within the EU, Germany, who see themselves as frontrunners when tackling the climate crisis [4–6]. The EU aims to be climate neutral by 2050 [7]. Germany, the EU's largest economy, intends to achieve climate neutrality by 2045 [8]. This target, as well as a yearly greenhouse gas (GHG) emission limit per sector are specified in the "Climate Protection Law" (*Bundes-Klimaschutzgesetz*, KSG) [9]. While attainable if swift and immediate actions are taken, these targets put considerable pressure to decarbonize on all economic sectors [10, 11].

A major obstacle on the path to climate neutrality arises from the uniqueness of this challenge. So far, the only countries to have reached climate neutrality are Bhutan and Suriname, but both are largely forested and sparsely populated [12]. Hence, there are no examples of how to manage such a transition and reach climate neutrality without these specific conditions, neither in the past nor in the present. Furthermore, it is not an isolated problem in one part of the economy [13]. Rather, all sectors are interconnected through a network of supply and demand and other interactions, and all of them need to reduce their emissions significantly [14].

One of the sectors particularly under pressure is the industry. In Germany, almost a quarter of CO_2 emissions stems from industrial activities [14]. Because of the variety of industrial processes, industry is particularly challenging to decarbonize [15, 16]. Further difficulties arise from the long-lived capital assets, high-temperature heat requirements, process emissions, and the international trade of industrial products [17]. Regardless, the German industry's emission budget shall decrease from 182 Mt-CO_2-eq in 2021 to 118 Mt-CO_2-eq. in 2030 and zero in 2045, as specified in the KSG [9]. This constitutes a much faster decline than in recent history: Between 2000 and 2021, GHG emissions in the industry only decreased by less than 13% [14]. Although the industry saw efficiency gains during this time, industrial growth cancelled out further reductions [18]. To still reach the specified emission targets in 2030, the average yearly decrease between 2022 and 2030 would have to be a magnitude higher than between 2011 and 2021 [19]. With current climate policies, emissions in 2030 would add up to 155 Mt-CO_2-eq, 37 Mt more than permitted [20]. Thus, identifying strategies to decarbonize industry within this limited timeframe is crucial.

1.2. Research aim

To be able to identify these strategies and map out the uncharted territory that the climate transition is, researchers often employ scenario planning and modeling. A scenario is a "coherent, internally consistent and plausible description of a possible future state of the world" [21]. Scenarios are able to provide guidance and give insights on how to conduct the climate transition: by capturing "the richness and range of possibilities," they can "stimulate decision makers to consider changes they would otherwise ignore" [22].

The aim of this thesis is to develop decarbonization scenarios for the German industry that can illustrate possible futures. To address interactions between different sectors and developments, a systems perspective is important. Therefore, the scenarios intend to display other developments as well, which have an influence on the decarbonization of industry. By doing so, they go beyond a mere technical dimension, but also include factors like societal trends or political development. As they are based on both storytelling and quantitative data, the scenarios aim to be tangible and understandable. Furthermore, it is also the goal to display futures that differ in multiple aspects, rather than varying individual factors. It does so by means of a cross-impact balance (CIB) approach, a specific scenario planning method. CIB offers a technique to utilize expert knowledge for the construction of scenarios that can display and take into account interactions between different future developments [23]. That way, consistent scenarios can be built. With these scenarios, it is the intention to achieve three objectives: to describe a range of possibilities, stimulate a debate, and, at best, provide guidance to stakeholders. Scenarios, as used here, are not a forecast, nor do they aim to predict the future [21]. They also do not assess the probability of one future over another.

The present thesis is part of the "Decarbonization and Electrification Potentials in the German Industry" (*Dekarbonisierungs- und Elektrifizierungspotentiale in der deutschen Industrie*, IND-E) project, which was commissioned by the Federal Ministry for Economic Affairs and Climate Action [24]. The project consortium consists of members from the Oeko-Institut in Freiburg, the Offenburg University of Applied Sciences, the Department of Sustainable Systems Engineering (INATECH) at the University of Freiburg and the Fraunhofer Institute for Solar Energy Systems (ISE) [24]. Currently, the group is working to identify decarbonization and electrification potentials in the German industry. The project is also planning to utilize a series of coupled energy system models to describe different paths the industry could take on their way to decarbonization, and to analyze their effects on the electricity grid and on unit commitment [18]. The scenarios developed here will be used in the IND-E project as input for REMod, one of the models, and subsequently in two other models. A detailed description of REMod's mechanics can be found in [25].

This paper is structured as follows: First, chapter 2.1 provides an overview of scenario development and two different scenario planning methods, Intuitive Logics (IL) and CIB. Then, in chapter 2.2., the German scenario planning literature will be reviewed, which leads to the identification of the research gap in chapter 3. After the presentation of the research gap and research questions, the methodology is described (chapter 4), followed by the results in chapter 5 and a discussion of method and results in chapter 6. Finally, chapter 7 presents the conclusions and an outlook.

2. Theoretical Background

2.1. Scenario development and modeling

Scenarios, as defined earlier, have a multitude of roles. According to Amer et al.'s review [26], scenarios and their consideration, among others,

- help to "conduct future planning in a holistic manner" [27, 28],
- improve the capacity to deal with uncertainty, as well as the "usefulness of the overall decision making process" [29, 30],
- "help us to be prepared for futures and innovate the futures" [31], and "question the future" [32],
- "provide an overall picture of the environment" and point out interactions between future events and trends [33],
- can identify and project the "consequences of particular choices or policy decisions" [34],
- describe a (possible) future situation and the path that leads to this future [35], and thus
- help to "make the desirable future real" [36].

Similarly, but more concise, Wright, Bradfield and Cairns [37] mention three key roles of scenario development: Firstly, to "enhance the understanding of the causal processes, connections and logical sequences underlying events — thus uncovering how a future state of the world may unfold" [37]. Secondly, to challenge conventional thinking, so that perceptions and mindsets can be changed. Thirdly, to improve decision making through informing strategy development [37]. With this diversity of goals, various methods to develop scenarios exist. The multitude of approaches has led scientists to even describe the different techniques as a "methodological chaos" ([38] as cited in [39]). Nevertheless, efforts are made to classify the diverse practices. For example, Bishop et al. [40] proposed eight general categories, with each having two to four variations (Table 1). In practice, processes from different categories are often combined. Still, such a list can help to clarify some confusion regarding scenario techniques [40].

Like scenarios, the role of models can be ambiguous too. Quantitative models are simplified mathematical representations of reality [41].[1] Often, they are seen as part of scenario planning, or even a scenario planning technique in its own [26, 39, 40]. Other times, modeling is a distinct step that can give more detail to a scenario [43]. Through models, one can assess whether a system envisioned in a scenario can exist under current assumptions, and what developments would be required for that. In other words, models translate scenarios into "projected consequences," whereas scenarios describe potential futures [43]. In this thesis, there is a clear distinction between scenario planning and modeling. This thesis develops scenarios, it does not, however, model them.

[1] Qualitative modeling also exists and can make structures in a system visible [42]. However, in this thesis, modeling refers to quantitative modeling.

Table 1. A categorization of different scenario construction techniques, as presented by Bishop et al. [40]. The abbreviation "T." stands for "The technique." See [40] for a more detailed elaboration, including the sub-categories.

Technique	Description	Sub-categories
Judgment	T. makes use of the judgment of individuals or groups to describe the future. It is a simple and straight-forward technique. Both unaided judgments and aided judgments occur.	Genius forecasting, visualization, role playing, Coates and Jarratt
Baseline/expected	T produces one scenario: expected/baseline. Typically, it applies an extrapolation of past trends into the future.	Trend extrapolation, Manoa, systems scenarios, trend impact analysis
Elaboration of fixed scenarios	Scenarios are decided before the process. Then, participants only need to "articulate implications of [the] given alternative futures" [40].	Incasting, SRI
Event sequences	T. visualizes the future as a series of events, each having a specific probability to occur. Events lead to other events, initiating a probability tree that scenarios are made of.	Probability trees, sociovision, divergence mapping
Backcasting	Instead of forecasting from the present, backcasting runs the other way. Starting from a certain given future state, one works themselves back to the present, asking what it would need to reach the future state.	Horizon mission methodology, Impact of Future Technologies, future mapping
Dimensions of uncertainty	T. identifies the biggest sources of uncertainty and develops scenarios based on those, depending on how the uncertainties take place.	Morphological analysis, field anomaly relaxation, GBN, MORPHOL, OS/SE
Cross-impact analysis	T. is based on the premise that events are related to each other, and that they can make it each other's occurrence more or less likely. Assessing the conditional probability of an event's occurrence, scenarios are developed by running models based on these probabilities of occurrence.	SMIC PROF-EXPERT, IFS
Modeling	Through varying the inputs and/or structure of the models, scenarios can be generated.	Trend impact analysis, sensitivity analysis, dynamic scenarios

To give a more detailed picture of scenario planning, the next section introduces two scenario planning methods: Intuitive Logics (IL) and cross-impact balancing (CIB). In Bishop et al.'s categorization, IL is typically a mix of *Judgment* and *Dimensions of uncertainty* methods, while CIB combines *Judgment* and *Cross-impact analysis* techniques [40]. IL was selected because it is the dominant approach in scenario planning [39, 44]. CIB provides a combination of quantitative and qualitative data and contains elements of other methods [23]. Furthermore, CIB is the approach chosen in this thesis, as outlined in chapter 3.

2.1.1. Intuitive Logics (IL)

Intuitive Logics (IL) is regarded the "mainstream scenario approach" ([45] as cited in [46], [39]). Similar to the "methodological chaos" in scenario planning as a whole, it is notable that there is no standard approach for IL [46]. Furthermore, the method continues to evolve [37, 44]. Still, Derbyshire and Wright [44] present a typical chronological order of steps, which is often followed in IL. In Stage 1 and 2, an issue of concern with its predetermined elements and critical uncertainties is identified. These critical uncertainties are at the center of the scenario analysis [45]. They are clustered into "related forces" in Stage 3, allowing for "causally linked," independent clusters [44]. Stage 4 identifies two "extreme but plausible" sets of outcomes per cluster. In Stage 5, those cluster outcomes with both a high impact and a high uncertainty are recognized. In the last phase, Stage 6, the two clusters with the greatest impact and uncertainty are identified and selected as the dimensions of the scenario [44]. This enables the 2 x 2 scenario method, where scenarios are varied over these two axes ([47], see also Figure 1). Here, it is important to note that two different arrays are possible: An either/or future, where only one of the two developments of the uncertainty factor is possible, or a more-less arrangement with more nuance [47]. In both cases, ideally, the approach then leads to "four diverse, yet plausible, causally-unfolded end-states" [44]. As scenario planners shift between different stages, IL is an iterative process [46]. Furthermore, the technique makes use of group discussions to arrive at scenario assumptions [44].

The advantages of IL lie in its straightforward approach [40]. Through focusing on the knowledge and assumptions of the scenario developers, it taps into an "intuitive understanding of future" [40]. Furthermore, the uncertainty pane widely used provides an adequate balance between technical sophistication and usability for a professional audience [40]. Thus, it is a straightforward and easy to communicate method. On the other hand, the technique also has disadvantages. With only two dimensions in the often used 2 x 2 scenario pane, it is almost impossible to accurately describe the future's uncertainty [40]. Moreover, the method has been demonstrated to be deterministic, as more "surprising" futures are usually not considered [48]. In doing so, the scenarios describe a range of potentially overly narrow pathways [37]. Additionally, these narrow futures can lead to increased confidence in the presented scenarios, which may be mistaken [49].

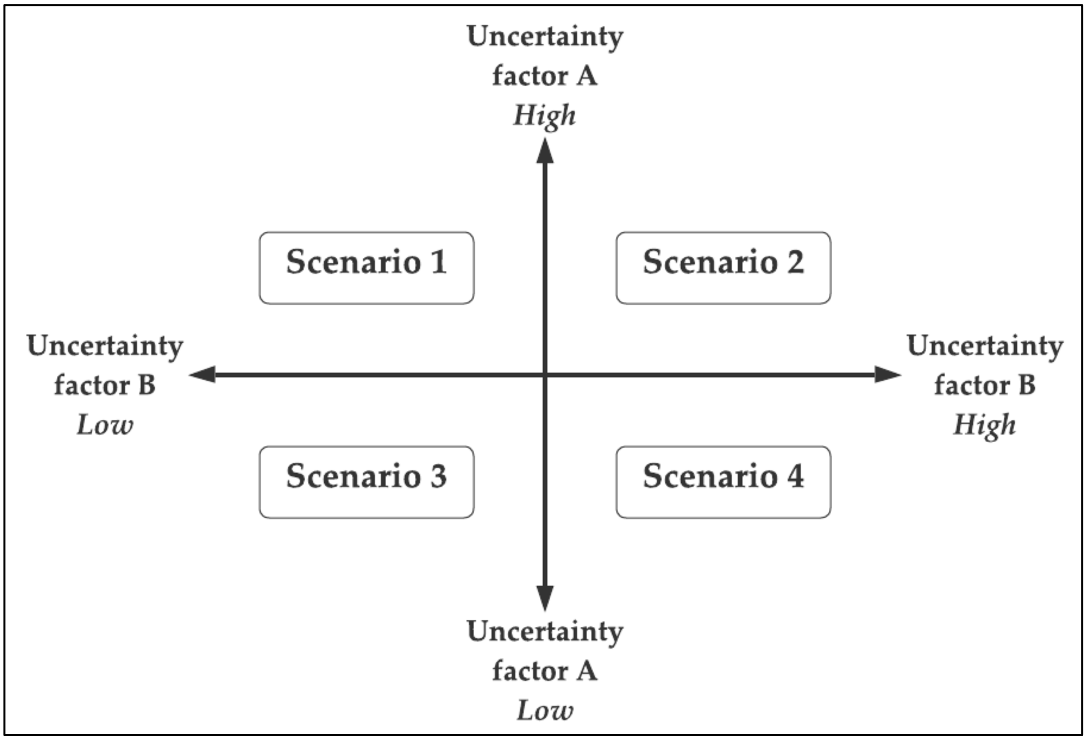

Figure 1. The 2 x 2 scenario pane in Intuitive Logics. Replicated from [46].

2.1.2. Cross-impact balance (CIB)

The cross-impact balance (CIB) method evolved out of cross-impact analysis (CIA), a scenario planning method used since the 1960s [23, 26]. It was first presented by Weimer-Jehle in 2006 [23]. Despite being relatively young, the CIB method has been applied in different fields, ranging from energy, urban planning or education to biotechnology [50]. For an extensive list of applications, see [50].

A CIB analysis begins with the establishment of a set of significant factors, so-called "descriptors," which can take on different future "states." Descriptors are defined as "(…) trends, events, developments, variables, or attributes that serve to describe the topic, frequently as proxies for influencing factors" ([51] as cited in [52]). In short, they are parameters, each describing a specific aspect of the future [52]. Different ways of identifying these descriptors exist, but they typically involve the consultation of experts. Then, for each descriptor, a set of 2-4 states is defined [53]. These states are intended to depict different possible developments per descriptor. A scenario is built up of one state per descriptor. While the many different possible combinations constitute one strength of the CIB approach, it also leads to an exorbitantly high possible number of scenarios.[2] However, some states have a restricting influence upon each other and are therefore less likely to appear in consistent scenarios [54]. If only those sets of states with the most promoting influences are to be considered, one can identify the consistent scenarios. To do so, expert input is utilized in combination with software analysis.

[2] For example, a set of 12 descriptors with 3 states each would lead to 3^{12} = 531,441 potential scenarios.

Before the assessment, it must be ensured that participants' interpretation of descriptors and states varies as little as possible. Hence, essays can be written to specify the meaning of the different elements. In the following step, experts are invited to assess the impact of each state on each state of all the other descriptors. All states of all descriptors are arranged in a matrix with all the states on both the x- and y-axis (Figure 2). Then, the experts assess the influences of the different states upon each other, typically using an integer scale ranging from a strongly restricting to a strongly promoting influence [53]. This leads to an array called cross-impact matrix (CIM).

After assessing the interconnections between the states, software is used to build the consistent scenarios [55]. The prepared matrix is used as an input. Then, for all possible combinations of different states, the software calculates an impact score. This means that for each selected state in a scenario, all positive and negative effects on each other state are added together. Then, per descriptor, the system examines whether another state would have a higher impact score. If that is the case, the scenario is considered inconsistent (Figure 2) [55]. If all selected states have the highest impact score of their descriptor, the scenario is considered fully consistent. The result is a set of consistent scenarios. In a final step, individual scenarios can be selected and presented in more detail by means of a storyline.

The greatest advantage of a CIB analysis is its ability to consider and display the interactions of different future developments in an efficient way. Through the expert input and the analysis done by the software, it is argued, the technique can utilize expert knowledge to recognize the impact pattern of the system and a mathematical method to analyze how this pattern works [23]. That way, the strengths of both human and machine can be employed [23]. Inconsistencies can be avoided, while still producing a high number of different scenarios. In addition, CIB's straightforward methodology has been mentioned as one of the key strengths of this approach [55]. It is comparatively easy to follow, does not require any modeling experience and assessments can be conducted by other experts. Lastly, CIB utilizes both qualitative and quantitative elements, and can therefore be well combined with modeling [23]. However, there are drawbacks to the approach as well. It is a time-intensive technique, which requires input from outside experts as well as a series of steps from the scenario planner [53]. Furthermore, the restriction to a limited number of descriptors means that analysis takes place at a high level [53]. Thereby, inevitably, some level of detail is lost. A last point of criticism is that, like other methods of scenario planning, the approach is also impacted by the subjectivity of participating experts [56].

Cross-Impact Matrix 'Somewhereland'	1. Gov			2. FoP			3. Eco			4. DisW		5. SCo			6. SoV		
	1a "Patriots party"	1b "Prosperity party"	1c "Social party"	2a Cooperation	2b Rivalry	2c Conflict	3a Shrinking	3b Stagnant	3c Dynamic	4a Balanced	4b Strong contrasts	5a Social peace	5b Tensions	5c Unrest	6a Meritocratic	6b Solidarity	6c Family
1. Government																	
1a "Patriots party"				-2	1	1	0	0	0	0	0	-2	1	1	0	0	0
1b "Prosperity party"				2	1	-3	-2	-1	3	-2	2	0	0	0	2	-1	-1
1c "Social party"				0	0	0	0	2	-2	3	-3	2	-1	-1	-2	2	0
2. Foreign policy																	
2a Cooperation	0	0	0				-2	1	1	0	0	0	0	0	0	0	0
2b Rivalry	0	0	0				0	1	-1	0	0	1	0	-1	0	0	0
2c Conflict	3	-1	-2				3	0	-3	0	0	3	-1	-2	-2	1	1
3. Economy																	
3a Shrinking	2	1	-3	0	0	0				-2	2	-3	1	2	0	0	0
3b Stagnant	-1	2	-1	0	0	0				0	0	0	0	0	0	0	0
3c Dynamic	0	0	0	0	0	0				-2	2	3	-1	-2	0	0	0
4. Distribution of wealth																	
4a Balanced	0	0	0	0	0	0	0	0	0			3	-1	-2	-2	1	1
4b Strong contrasts	0	-3	3	0	0	0	0	0	0			-3	1	2	2	-1	-1
5. Social cohesion																	
5a Social peace	0	0	0	0	0	0	-2	-1	3	0	0				2	-1	-1
5b Tensions	0	0	0	-1	0	1	1	1	-2	0	0				-1	0	1
5c Unrest	2	-1	-1	-3	1	2	3	0	-3	0	0				-2	-1	3
6. Social values																	
6a Meritocratic	0	3	-3	0	0	0	-3	0	3	-3	3	-2	1	1			
6b Solidarity	1	-2	1	0	0	0	-1	2	-1	2	-2	2	-1	-1			
6c Family	0	0	0	0	0	0	-1	2	-1	1	-1	2	-1	-1			
Impact scores	0	3	-3	2	1	-3	-9	-1	10	-7	7	4	-1	-3	2	-1	-1

An evaluation field

The impact score of a variant

An inconsistent state (4a) has been selected for this variant, as state 4b has a higher impact score than the selected one.

The impact balance of a descriptor

Figure 2. This example shows a cross-impact matrix (CIM) with the impact balance of an inconsistent scenario at the bottom. Impacts point from the x-axis towards the y-axis and are measured as follows: -3 – strongly restricting influence, -2 – moderately restricting influence, -1 – weakly restricting influence , 0 – no influence, 1 – weakly promoting influence, 2 – moderately promoting influence, and +3 – strongly promoting influence [55]. The selected states for the inconsistent scenario are indicated by the gray highlighting in the CIM. The impact scores are calculated by adding up the individual assessments of the selected scenario for the specific column. For descriptor 4, state 4b has a higher impact score than the selected state 4a. Adapted from [55].

2.1.3. Comparing IL and CIB

The CIB method and IL are similar in that they both make use of judgments of groups or individuals for the construction of their scenarios [40]. They are also both qualitative methods, even though in CIB, this is combined with a quantitative element [23]. CIB has a more clearly defined methodological structure, which is easy to follow. This structure can also be disadvantageous, as a CIB analysis requires significantly more resources than IL [57]. While both approaches are straightforward and can be adjusted to the requirements of the researcher, IL is more flexible and makes more use of human creativity [46]. However, compared to an IL approach that utilizes a 2 x 2 scenario pane, more variation in scenarios is possible with CIB. Moreover, a CIB approach is better able to consider interactions between possible future events, as this is inherently part of the method [23].

Although CIB has been utilized in different fields [50], IL is the most common scenario planning approach [39, 45]. Correspondingly, the extensive system studies in Germany have typically used variations of the IL approach. These system studies are presented in the following section.

2.2. System studies in Germany

As shown earlier, there is a need for scenario development of a future carbon-neutral German energy system. Different learning rates of technologies, economic or political developments, public attitudes and many other components can shift the balance and make one pathway more favorable than the other. To take into account these interactions, a systems perspective is preferable over approaching the transition of industry as an isolated problem [13]. Therefore, this section reviews system studies rather than industrial studies. For recent studies reviewing the decarbonization of individual industrial sectors, see [58–65]. In Germany, five studies, also called the "Big Five" [66], recently developed scenarios and modelled the possible pathways of the energy transition. Another study by the Fraunhofer ISE investigated the impact of different societal developments. These studies were all published in 2021, thereby providing an up-to-date analysis from different stakeholders. An overview of the most important characteristics of the Fraunhofer ISE study and the "Big Five" be found in Table 2. The following paragraphs provide summaries of these studies.

Like most of the "Big Five" the analysis from the Fraunhofer ISE modeled the German path to climate neutrality in 2045. The study stands out in the that it varied between different paths the society could take. Here, societal acceptance of climate change technologies, a restriction of demand and corresponding parameters differed per modeled world. This led to scenarios named "nonacceptance," "persistence," "reference," and "sufficiency" [67]. Despite developing four scenarios, they did not operate with the 2 x 2 pane to vary between scenarios. Mostly, these changes were depicted in different combinations of consumption patterns. However, scenario "nonacceptance" also employed a lower upper limit for wind energy and electricity imports. Among others, the study found that behavioral change can have a large impact on the transformation of the energy system. On the one hand, a backlash

Table 2. An overview of studies realizing a carbon-neutral future in Germany in 2045/50 [11, 18, 25, 68–70]. Titles and commissioner translated to English.

Study on behalf of	Organization conducting study	Title	Scenarios considered	Target year climate neutrality
Federal Ministry for Economic Affairs and Climate Action	Fraunhofer Institute for Systems and Innovation Research ISI, Consentec GmbH, ifeu – Institute for Energy and Environmental Research, Chair of Energy and Resource Management TU Berlin	Long-term scenarios for the transformation of the energy system in Germany	Total of nine scenarios, three main scenarios: • Electrification • Hydrogen • Synthetic hydrocarbons	2050
German Energy Agency (dena)	Institute of Energy Economics at the University of Cologne (EWI), ITG Institute for Building Systems Engineering Research and Application, Jacobs University Bremen (JUB)	dena pilot study: Towards climate neutrality	One main scenario "Climate neutrality 100" (KN100) and four path variations: • More electrons • More molecules • Efficient electrons • Efficient molecules	2045
Federal Association of the German Industry (BDI)	Boston Consulting Group (BCG)	Climate Paths 2.0. An economic program for climate and future	One target path	2045
-	Copernicus Project Ariadne, Potsdam Institute for Climate Impact Research (PIK)	Germany on the path to climate neutrality in 2045. Model comparison of scenarios and pathways	One trend and six technology scenarios, clustered in: • Balanced technology mix • Direct electrification (domestic and import) • Hydrogen (domestic and import) • E-fuels • Trend	2045
Climate Neutrality Foundation, Agora Energiewende, Agora Verkehrswende	Prognos AG, ÖkoInstitut e.V., Wuppertal Institute for Climate, Environment, and Energy	Climate-neutral Germany in 2045. How Germany can achieve its climate targets before 2050.	One scenario, Climate-neutral Germany 2045	2045
-	Fraunhofer Institute for Solar Energy Systems ISE	Pathways to a climate-neutral energy system. The German energy transition in the context of societal behaviors	Four scenarios, varying societal trends: • Persistence • Nonacceptance • Sufficiency • Reference	2045

would make the realization of Germany's climate targets more difficult and more expensive, but not impossible. On the other hand, a shift towards more sufficient behavior could save €1.3 trillion of investment compared to a reference scenario until 2045 [25].

In cooperation with other institutes and commissioned by the Federal Ministry for Economic Affairs and Climate Action, the Fraunhofer Institute for Systems and Innovation Research (ISI) developed so-called "long-term scenarios" (*Langfristszenarien*). Using the old KSG targets – 100% GHG emission reduction by 2050 and 95% for the industry sector – as conditions [71], it was the only "Big Five" study to apply the 2050 target. Most recently, they published scenarios aiming for 2045, which could not be included for review anymore [72]. Their assumptions were taken based on statistical data, empirical studies, academic literature and expert judgement [68]. They applied some variation of an IL approach. Through variation of assumptions regarding the use of different energy carriers, they then modelled nine different scenarios. Three of these were "main scenarios" with one dominant energy carrier (electricity, green hydrogen, and synthetic fuels), respectively. Other assumptions regarding economic growth, carbon capture and storage (CCS) or the use of biomass were not varied. They found that in some use cases, one technology was clearly preferred, while in others, multiple technological solutions seem possible [71]. Electrification seemed to be a robust strategy for heat in a large share of the built environment, and for a big portion of the individual transport and heavy transportation. Power-to-Gas and Power-to-liquid (summarized under PtX) appears necessary for air and maritime traffic. Different technologies could be possible for poorly insulated buildings, long distance transport and process heat and industrial processes. Here, they emphasized the necessity to choose technologies and remove obstacles through policies. Comparing the three main scenarios, electrification is by far the least expensive, with additional costs of €250 billion and €370 billion until 2050 for the hydrogen and PtX scenarios compared to electrification, respectively.

The Ariadne Project, which consists of scientists from different German institutes and universities, also modelled scenarios with a focus on direct electrification, hydrogen, and e-fuels. In addition, they ran a "balanced technology mix" and a "trend" scenario [69]. They, too, presumably utilized an IL methodology, but do not specify so in their reports. Varying between different models, they answered specific research questions by using the model best suited for the task [69]. They found that a faster electrification requires especially a faster transformation of final energy use, while for a focus on hydrogen or PtX, a quick increase in production capacity and associated infrastructure is needed. The study also found the climate targets to be exceptionally challenging. Without significant efforts, the 2030 goal would be missed, and subsequently the 2045 target as well [69].

The Institute of Energy Economics at the University of Cologne (EWI), commissioned by the German Energy Agency (*Deutsche Energie-Agentur GmbH*, dena), was the main evaluator in yet another report. In a multi-stakeholder approach with industry as well as other scientists, EWI defined assumptions and boundary conditions, which were then used in different bottom-up models. They developed a main scenario, with an "electrons" (electrification) and a "molecules" (hydrogen and synthetic fuels) variation [11]. The group further distinguished between a more optimistic and a less optimistic efficiency development, leading to five different scenarios (the main scenario and four alternative scenarios). Thus, this was the only study to use a 2 x 2 pane. The scenarios mostly differed in the assumed efficiencies of key technologies. Using a bottom-up model, choices regarding technologies could easily be made by the model operators. Compared to the other studies, climate neutrality is achieved with only few negative emissions from direct air carbon capture and storage (DACCS) and bio-energy with carbon capture and storage (BECCS). They also assumed significantly lower efficiency gains in industry than, e.g., the study by Fraunhofer ISI [11, 68]. Higher assumptions regarding the natural storage of CO_2 through land use, land use change and forestry (LULUCF, 41 Mt-CO_2-eq.) and the highest import assumptions for hydrogen (400 TWh) make up for this gap [66]. Other findings were consistent with the other studies, showing a strong (41%) decrease of final energy until 2045 and a key role for electricity and hydrogen [11].

A consortium of Prognos, Oeko-Institut and Wuppertal Institute conducted a cost optimization study on behalf of Agora Energiewende, Agora Verkehrswende and the Climate Neutrality Foundation. They constructed a normative scenario, i.e., only one "ideal" path to reach climate neutrality in 2045. In their report, they expect a fast development of hydrogen technologies, renewable energies and climate protection technologies rather than higher efficiency increases, which take longer to materialize. Compared to a previous analysis, where the group applied the old 2050 target, measures, new technologies, procedures and infrastructure all need to be implemented significantly faster when aiming for 2045 [70, 73]. Therefore, they identify their pathway as a technology scenario [70]. Although they aimed to minimize the use of CCS and focus on technologies with low technical and economic risks, their scenario employs the highest amount of BECCS and DACCS technology of the "Big Five" [66]. This is likely connected to their assumptions, in which they adopt the highest GDP growth of all five studies, while also utilizing a different approach regarding the carbon storage capacity of LULUCF: They exclude LULUCF from their CCS calculations, as they are uncertain of the storage function of German forests in light of climate change [70]. This makes their results more robust in that regard, but also requires more BECCS and DACCS.

The Boston Consulting Group (BCG) commissioned by the German Industry Association (*Bundesverband der deutschen Industrie*, BDI) published a report that also developed a normative scenario to achieve climate neutrality by 2045 [18]. To acquire and validate their results, they worked with and interviewed experts from industry. An advisory board of scientists and employee representatives was consulted for "central questions" [18]. One main result is that key infrastructure needs to develop much quicker than currently planned. According to BCG, the German grid development plan (NEP, *Netzentwicklungsplan*) for 2035 has to be moved forward by five years. Additionally, in 2030, they expect significantly more hydrogen than planned in the German national hydrogen strategy. Generally, a focus is put on government financing. A crucial difference to ISI's conclusion is BCG's appeal to not take a decision for or against specific technologies or measures, in order to be able to react flexibly to unexpected developments [18, 68].

Despite having different assumptions and results, all five studies came to some common conclusions. In all cases, the final energy consumption goes down significantly: When accomplishing climate neutrality, final energy consumption reaches around 45% reduction compared to 2018, with one exception of around 55% reduction [66]. Moreover, electrification plays an important role everywhere, although the share of electricity in final energy consumption varies between 46 and 69% in 2045 [66]. Except for one Ariadne scenario, all studies assumed similar developments regarding economic growth and consumption behavior. The papers all calculated with steady economic growth of about 1%, and usually did not expect strong societal changes, except for the Fraunhofer ISE study. A shared finding was also the accelerated coal phase-out for electricity production as compared to policy targets by the time. According to these government plans, all coal power plants should be turned off by 2038 [74].[3] In the studies by BCG, Ariadne, and Prognos, coal phase-out was completed by 2030 [18, 69, 70]. In the paper commissioned by dena, it was conducted "well before 2038" [11]. Solely, the ISI study did not specify the date of the coal phase-out, but left coal as an option for the optimization model until 2038. Remarkable is also the "market-driven" phase-out, which some studies mention [11, 70]. Another similarity is that in all studies, steel is typically produced with a roughly equal share of recycled steel and hydrogen direct reduction [66]. The quantities produced are similar to today.

The studies employed a combination of the different scenario planning techniques identified by Bishop et al. (Table 1, [40]). All reports used backcasting, as they all started with the premise of reaching climate neutrality in 2045/50. They all utilize judgment techniques, where groups or individuals are consulted to describe the future. Moreover, every analysis models their scenarios and varies the inputs, thus using modeling as well. The two studies from BCG and Prognos developed normative studies, while the other ones described multiple futures. The only study to apply a 2 x 2 pane was the one commissioned by dena. Thus, the papers apply a wide mix of techniques.

With their description of different futures, the "Big Five" and the ISE study show different paths towards climate neutrality. However, what is lacking in all these studies, is a thorough account of how the researchers constructed their scenarios. Although personal conversations revealed that, for instance, the "long-term scenarios" from Fraunhofer ISI apply a Story-and-Simulation (SAS) approach, a variation of the judgment technique [76], these steps are barely described in their papers, if at all. This holds true for the other studies as well, where the methods of arriving at the specific scenarios remain unclear or are not described in detail, except for the modeling part. In doing so, they only partly achieve the three key roles of scenario development, as outlined by Wright, Bradfield and Cairns [37]:

[3] The present government aims for a phase-out by 2030, if feasible, but this has not been put into law (yet) [75].

1) "*Enhancing understanding*: of the causal processes, connections and logical sequences underlying events — thus uncovering how a future state of the world may unfold;
2) *Challenging conventional thinking*: to reframe perceptions and change the mindsets of those within organizations; and
3) *Improving decision making*: to inform strategy development" [37].

With the prominent role of the scenarios in the German discourse,[4] the studies are certain to inform strategy development and thereby improve decision making. By means of their scenarios, they also "uncover how a future state of the world may unfold" [37]. However, they fail to explain the causal processes and connections behind the underlying events, as the scenario construction is explained only briefly, if at all. Thirdly, by constructing overly narrow pathways or similar scenarios with comparable methodologies, they do not all challenge conventional thinking.

[4] This is demonstrated, for example, by the participation of the state secretary of the Federal Ministry for Economic Affairs and Climate Action at the presentation of new results of one of the "Big Five" [72].

3. Research Gap and Research Questions

Through the only partial fulfillment of the key roles of scenario development, a research gap emerges. It is the goal of this thesis to develop scenarios that fulfill all three roles and thus to enhance the understanding of the "processes, connections and logical sequences" that lead to a future state, to challenge conventional thinking by using a different approach and to improve decision making [37]. As outlined in chapter 1.2, it is the intention to do so through developing decarbonization scenarios for the German industry with a CIB approach. CIB takes into account interactions between different developments, thereby producing internally consistent scenarios. It also offers a combination of qualitative and quantitative data, which fits well with the purpose of modeling the scenarios at a later stage in the IND-E project. In combination with the research aim, developing decarbonization scenarios for the German industry, this leads to the following main research question (MRQ):

Which consistent scenarios can depict different futures of a carbon-neutral German industry in 2045?

From this, the following sub-questions (RQ1-5) emerged, which were answered with a CIB analysis:

1. Which factors affect the decarbonization of the German industry?
2. Which developments could these factors take?
3. What is the impact of these factors upon each other?
4. Which consistent scenarios of decarbonizing the German industry until 2045 are possible?
5. Which scenarios can be chosen to depict different possible futures?

4. Methodology

To develop consistent scenarios of different worlds that describe the German (industry's) path to climate-neutrality and answer the research questions, this paper utilized the CIB approach [23]. First, descriptors and states were constructed, followed by essays describing them. In a next step, expert workshops were conducted to create a cross-impact matrix (CIM). From this, consistent scenarios were identified with ScenarioWizard 4.4[5] and subsequently, four of them were selected and illustrated in short descriptions. The following chapter provides more detail on these steps. An overview of the process can be seen in Figure 3.

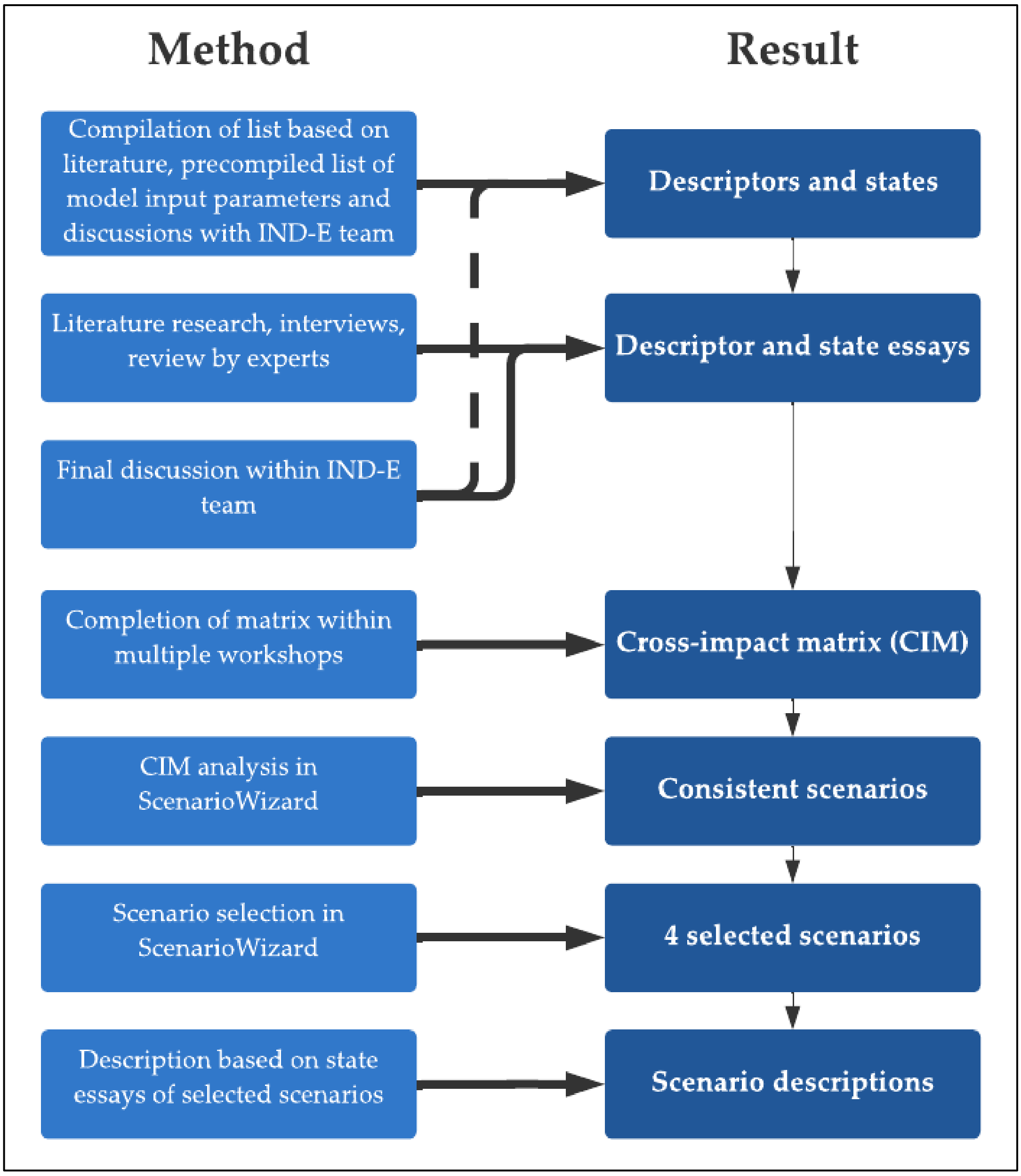

Figure 3. A schematic overview of the methodological steps taken.

[5] ScenarioWizard is a software developed by Wolfgang Weimer-Jehle for the execution of a CIB analysis. In ScenarioWizard, matrices can be created and analyzed. It is available for download under [77].

4.1. Selection of descriptors

The first step of a CIB analysis requires the selection of a set of descriptors. In this research, the descriptors also answered RQ1.[6] Determining the descriptors is a crucial element of CIB analysis, as they determine the context elements included and omitted [57]. Furthermore, some of the descriptors should be "coupling descriptors" that constitute model input [53]. Hence, the set of descriptors is composed of a mix of qualitative and quantitative factors. A set of rules was defined for the development of the descriptors. Firstly, only relevant descriptors were selected. In this case, relevant meant that they had to be either relevant for the decarbonization of the industry, or for the climate transition generally, or both. Secondly, the descriptors could not describe outcomes of models used in the IND-E project. Rather, if directly relevant to the models, they had to be model input. An example of such an excluded descriptor is the expansion of renewables. Although highly relevant, it is a model output of REMod, and was therefore excluded. Thirdly, the total number of descriptors had to be between 10 and 15. CIB analyses typically have between 10 and 20 descriptors [53]. Too many descriptors make the matrix overly complicated and lengthen the evaluation process. In contrast, too few are not able to give an adequate portrayal of the future. Therefore, and in accordance with literature, the number was set to 10 to 15 descriptors.

After defining the general conditions, the descriptors were constructed in a multi-step process. A list of model input parameters constituted initial input. IND-E project participants had compiled the list before the start of this thesis. It contained relevant input parameters for the model, some of which were to be defined by the descriptors and the according states. The list can be found in Appendix A. In addition, descriptors from CIB literature with related research topics were scanned. Specifically, descriptors from Pregger et al. [57], Vögele et al. [78], and Senkpiel et al. [79] were compared. Then, an expanded list of 29 descriptors was compiled (Appendix B). Next, descriptors were grouped together or removed. After consultations with the IND-E team, a preliminary list of descriptors remained. These descriptors and their according states underwent a final discussion and adaptation of the scientists of the IND-E project at a workshop on 13 October 2022.

4.2. Definition of descriptor states

The definition of the descriptor states took place simultaneously with the development of the descriptors. Based on literature, expert interviews and consultations, states were developed for all descriptors. Typically, a CIB analysis operates with two to four states [53]. Here, two or three states were added to each descriptor. For six descriptors, these states illustrate the two extremes between quick/timely/high/ambitious and slow/delayed/low/unambitious. For the six other descriptors, a state in between these extremes was added to convey more nuance. Like the descriptors, the states too were discussed

[6] RQ1: Which factors affect the decarbonization of the German industry?

throughout the process and eventually, some were slightly adjusted during the workshop on 13 October 2022. These adjustments can be seen in Appendix C and D.

4.3. Descriptor and state essays

One of the key elements of a CIB analysis is the definition of descriptors and states in short essays. These essays serve multiple purposes: The descriptor essays introduce the descriptors and clarify the meaning of a specific descriptor [55]. The state essays explicate the states, so that experts filling in the CI matrix can visualize them [55]. As the level of ambiguity varied per descriptor, so did the length of the essays. Sometimes, quantitative assumptions were made, which couples the scenario planning process with the modeling. They supported the experts in their judgment, but will also be relevant to the IND-E project in the modeling phase. These different conditions led to essays describing a mix of quantitative variables, qualitative storytelling and to some extent, an explanation of concepts used. In this thesis, the essays answered RQ2 as well and helped to construct storylines for scenarios in a later stage.

For writing them, a mixed approach was chosen: Five unstructured interviews with experts complemented desk research. A list of experts and topics discussed can be found in Table 3. Thus, based on interviews and a literature review, a draft version was compiled. Then, the essays were sent out to the IND-E team and participating experts for review and subsequently edited. The adjusted essays were presented at the project workshop on 13 October, where the IND-E team discussed the content of the essays. Some assumptions – quantitative and qualitative – were adjusted, others removed. Following this discussion, essays were adapted to their final version.

Here, it is important to note that the detailed elaboration of what is considered quick/timely/high/ambitious versus slow/delayed/low/unambitious was made based on scientists' views. Other stakeholders involved in the climate transition (e.g., politicians, entrepreneurs, or citizens) might view these topics very differently.

Table 3. Expert interviews conducted for the composition of descriptor and state essays.

Experts interviewed	Institute	Date	Topic
Franziska Riedel	Fraunhofer ISE	26.07.2022	Corporate strategies
Julian Brandes	Fraunhofer ISE	28.07.2022	Market entry of industrial decarbonization technologies, Quantitative descriptors
Jessica Berneiser, Johanna Kucknat, Franziska Riedel, Moritz Vogel	Fraunhofer ISE, Öko Institut	02.08.2022	Climate policies, Societal development
Markus Kaiser	Fraunhofer ISE	04.08.2022	Implementation of descriptors in REMod, Market entry of industrial decarbonization technologies, Fossil fuel prices, PtX import potentials, PtX import prices
Matthias Rehfeldt, Thurid Lotz	Fraunhofer ISI	09.08.2022	Industrial relocation, Circular economy

4.4. Cross-impact matrix (CIM)

After completion of descriptor and state essays, the filling-in process for the cross-impact matrix (CIM) could commence (RQ3). As mentioned earlier, in the CIM, the researcher arranges all states of all descriptors in a matrix. Then, experts fill in the matrix by estimating the influence of each state on all states from other descriptors. Typically, an integer scale from -3 to +3 is used [54]. Within this thesis, the same approach was applied (Table 4).

Table 4. The CIM scale used in this thesis [54]. Low values indicate a restricting influence, while high values indicate a promoting influence.

Value	Influence
-3	Strongly restricting influence
-2	Moderately restricting influence
-1	Weakly restricting influence
0	None
1	Weakly promoting influence
2	Moderately promoting influence
3	Strongly promoting influence

A set of rules made sure that the experts were filling out the matrix according to the principles of CIB:

- Influences were only assessed in one direction, i.e., from state x of descriptor X upon state y of descriptor Y. The opposite direction was considered when assessing state y of descriptor Y's impact [23].
- Only direct influences were to be assessed. Resulting indirect influences were constructed by ScenarioWizard during the evaluation [54].
- If no influence could be found or the experts could not agree on a value, a "0" was to be filled out [54].
- The overarching target of building scenarios that can reach climate neutrality in 2045 was not to be considered when assessing influences. For example, low import potentials of PtX products should **not** be assessed as promoting a timely expansion of the electric grid, in order to compensate for less PtX products by a stronger electrification.

The influences of the different states upon each other were evaluated in a series of four workshops. Groups of usually three, but at least two and at most four experts assessed the influences of all the states of one descriptor on all the states of another descriptor together (Table 5). Descriptors were assigned based on self-assessed expertise of the chosen experts.

Table 5. An overview of the experts and the descriptors that they filled out in the CIM.

Group members	Institutes	Date	Descriptors filled out
Jessica Berneiser, Susanne Krieger, Mirko Schäfer	Fraunhofer ISE, Öko Institut, INATECH	13.10.2022	Societal trends
Hanhee Kim, Ramiz Qussous, Charlotte Senkpiel	HS Offenburg, INATECH, Fraunhofer ISE	13.10.2022	Fossil fuel prices, Power grid expansion
Gregor Gorbach, Christoph Heinemann, Markus Kaiser, Franziska Ossenkopp	Fraunhofer ISE, Öko Institut,	13.10.2022	Market entry of industrial decarbonization technologies
Julian Brandes, Susanne Krieger, Christoph Heinemann	Fraunhofer ISE, Öko Institut	17.10.2022	Hydrogen infrastructure
Cesar De Jesus Tabora, Markus Kaiser, Ramiz Qussous	HS Offenburg, Fraunhofer ISE, INATECH	17.10.2022	Negative and residual emissions
Gregor Gorbach, Franziska Ossenkopp, Charlotte Senkpiel	Fraunhofer ISE, Öko Institut	17.10.2022	Corporate Strategies
Matthias Rehfeldt, Meta Thurid Lotz	Fraunhofer ISI	21.10.2022	Industrial relocation, Circular economy
Franziska Ossenkopp, Mirko Schäfer, Charlotte Senkpiel	Öko Institut, Fraunhofer ISE, INATECH	24.10.2022	Climate policies
Cesar de Jesus Tabora, Markus Kaiser, Susanne Krieger	HS Offenburg, Fraunhofer ISE, Öko Institut	24.10.2022	Import potentials of PtX
Julian Brandes, Gregor Gorbach, Ramiz Qussous	Fraunhofer ISE, INATECH	24.10.2022	PtX import prices

A Google Sheets spreadsheet was shared, in which each group could fill in the estimated influences. When filling in, experts were encouraged to leave comments in the Google Sheets file. This way, reasoning of groups could be backtracked. If required, the groups could be asked for clarification or to redo some of their work, when the reasoning was unclear or when the group did not follow the CIM guidelines. For example, one group redid parts of their matrix, as they assumed that the system had to reach climate neutrality. However, not all groups made use of the comment option, and most only left comments for some descriptors. The original Google Sheets file including comments can be found in Appendix E.

Filling in took place over the course of one and a half weeks and four distinct workshops. Participants were asked to read the descriptor and state essays beforehand. Additionally, all descriptors and states were presented and discussed at the beginning of the first workshop. Experts who had not participated in the first workshop were asked to read the essays and were given a presentation of methodology, descriptors, and states before the start of their workshop.

4.5. CIB analysis, scenario selection and scenario description

The resulting CIM was analyzed in ScenarioWizard 4.4 [77]. The CIM can be utilized to assess the significance of individual descriptors. This is performed by calculating the active and passive sums of descriptors [55]. As a measure of descriptor A's influence on descriptor B, the average absolute value of all cross-impact judgments per evaluation field is calculated and added up per descriptor [55]. The metric can display the extent of the direct influence of a descriptor on other descriptors and, vice versa, the extent to which other descriptors influence the particular descriptor [55]. Through doing so, direct influences – but not indirect influences – are shown.

ScenarioWizard 4.4 was also used for the identification and analysis of consistent scenarios (RQ4). Due to the uncertainty of the assessment of the CIM, an inconsistency value of one was deemed acceptable. This meant that scenarios were accepted, which incorporated states, where another state of the same descriptor had an impact score that was at most one point higher than the selected state (see Figure 2). Such an approach has also been chosen in other papers [80]. This led to 16 consistent scenarios with a maximum inconsistency value of one, of which four were chosen to depict different possible futures (RQ5). This number was based on literature: 3-5 future scenarios have been found to be appropriate for scenario developing, with 4 scenarios being the most typically employed number [26].

Scenarios were chosen to represent as many different states as possible. To do so, the selection technique "Residual" was used in ScenarioWizard [55]. This way, three scenarios that contain all different states occurring in the 16 consistent scenarios were selected. A fourth scenario was chosen, which combined specific states shown in the three other scenarios. When selecting, an attempt was made to also choose scenarios that seemed plausible to experts. This way ensured that scenarios were as different as possible, while remaining plausible. In a final step, storylines were written to describe the chosen scenarios qualitatively. The CIM was utilized to explain influences between the different states in the storylines.

5. Results

5.1. Descriptors and states

The final list of twelve descriptors and their respective states can be found in Table 6. This answers RQ1.[7] Two or three states, both occurring six times, were developed per descriptor. The states, and in particular the essays presented in chapter 5.2, give answer to RQ2.[8]

Table 6. The final list of the 12 descriptors and their respective states.

Descriptor	States
Climate Policies	Very ambitious climate policies Ambitious climate policies Unambitious climate policies
Fossil fuel prices	High fossil fuel prices Low fossil fuel prices
Power-to-X (PtX) import prices	High import prices Low import prices
Import potentials of PtX	High import potentials Medium import potentials Low import potentials
Hydrogen infrastructure	Timely expansion Delayed expansion
Power grid expansion	Grid expansion as currently planned Delayed expansion
Market entry of industrial decarbonization technologies	Quick market entry Medium-fast market entry Slow market entry
Circular economy and digitalization	Circular economy expanding Business-as-usual (BAU)
Corporate strategies	Ambitious corporate strategies Moderately ambitious corporate strategies Unambitious corporate strategies
Industrial relocation	Widespread relocation Moderate relocation Minor relocation
Negative emissions and residual emissions	Low number of negative and residual emissions High number of negative and residual emissions
Societal trends	Increasing consumption (BAU) Constant development Sufficiency behavior

[7] RQ1: Which factors affect the decarbonization of the German industry?
[8] RQ2: Which developments could these factors take?

5.2. Descriptor and state essays

5.2.1. Climate policies

In Germany, climate policies are defined by both national and EU legislation. The Federal Climate Change Act (*Bundes-Klimaschutzgesetz,* KSG) establishes the target of climate neutrality by 2045 and the in-between steps to reach this objective [9]. This national target is supported by the EU Emission Trading System (EU ETS). The EU ETS regulates issuance and trade of emission certificates in the European energy sector, in emission-intensive industries and in inner-European aviation, covering about 40% of the EU's GHG emissions [81]. In 2021, the European Commission (EC) proposed reforms to the EU ETS as part of the EU Green Deal. With the proposed EU Carbon Border Adjustment Mechanism (CBAM), the EC intends to reduce free allocation of cost certificates in these industries but still address carbon leakage through import taxation on certain carbon-intensive commodities [82].

There are also several other measures being discussed, for example, so-called Carbon Contracts for Difference (CCfDs). CCfDs subsidize the difference in investment costs and operating expenses of new technologies compared to, e.g., buying emission certificates [83]. They could encourage investments into carbon-reducing technologies before these are economically viable. On a national level, grid charges (*Netzentgelte*) are due to be reformed. Currently, the charging system benefits consumers with steady and high demand and places where there is *little* wind power [84]. This obstructs innovations and discourages flexibility to balance the grid. Another point of concern is the duration of approval procedures for industrial installations, which can take up to five years [85]. The long procedures slow down the implementation of new, carbon-free facilities in industry. Similarly, the delays hinder the expansion of renewable power generation projects [86]. Thus, reforming the grid charges and the approval procedures could lead to a significant acceleration of the energy transition.

5.2.1.1. Very ambitious climate policies

In the state *Very ambitious climate policies*, both supply and demand climate policies are introduced quickly and foster the transition to a climate-neutral society. On the demand side, policies promoting a reduction of energy demand are continued or introduced. Sufficiency behavior is fostered through instruments affecting infrastructure, mobility, and consumption of goods. Specifically, these include incentives for a more plant-based diet, the facilitation and provision of bike paths and public transport, reduced speed on highways, disincentivizing air travel, and promoting and enabling more sustainable ways of living. Higher efficiency is supported with policy interventions like ambitious efficiency standards, subsidized energy audits, building regulations, or targeted information programs [87].

Through the widespread application of CCfDs and other funding, companies are able to bring new technologies into the market. The EU ETS updates proposed by the EU in 2021 are introduced, including a faster decline of emission allowances until 2030, and other measures. CBAM is also implemented timely and effectively and is coordinated well with the allocation of certificates in the EU ETS.

Nationally, approval procedures are shortened: Personnel shortages in competent authorities are improved, and procedures follow a more standardized path; they are simplified, and deadlines are reduced. Accordingly, the average time for approval procedures reduces to 2-3 years. This applies for both industrial installations and renewable energy projects. Moreover, grid charges are being reformed. This benefits consumers located in areas with high production of RE. Consumers that can quickly ramp up or down their power consumption to balance the grid profit too. Together, these developments lead to a higher planning security for companies.

5.2.1.2. Ambitious climate policies

In the state *Ambitious climate policies*, a focus lies on climate policies for the supply of energy and goods. This state is identical to the state *Very ambitious climate policies*, with the difference that efficiency and sufficiency measures do not receive the same attention. CCfDs and other funding is still widely applied, and the EU ETS is reformed as described above. Approval procedures for industrial facilities and renewable energy production are shortened as well.

5.2.1.3. Unambitious climate policies

In this state, necessary reforms are not implemented, or implemented with delay. The proposed EU ETS updates are implemented in a weaker form only, leading to a lower reduction of emission certificates and a lower carbon price overall. Sufficiency behavior is not promoted beyond today's levels.

Nationally, approval procedures for industrial installations do not reduce in time, as the personnel shortages in the competent authorities continue and approval procedures remain complicated and are not reformed. This leads to a total average duration of 5 years for approval procedures in the industry and in large renewable energy projects. With the long processes, planning security does not increase. Similarly, grid charges are only reformed late (after 2027).

5.2.2. Fossil fuel prices

The price of fossil fuels (coal, gas, oil) is an important economic factor for industries, households, and government alike. At the same time, they are subject to a high degree of uncertainty caused by resource availability, changes in demand, global climate policies, and geopolitical events [88]. Particularly, the recent energy crisis has shown both the unpredictability and significance of fossil fuel availability and prices. In the future, two scenarios seem possible: A continuation of shortages due to uncertain supply chains, with high prices as a result, or a stabilization of prices at pre-crisis levels.

5.2.2.1. High fossil fuel prices

Geopolitical tensions continue in the long term, effectively preventing the import of cheap fossil fuels. Scarcity of natural gas continues, although efforts to decrease dependency on single producers lead to an improvement of the most urgent shortages. A diversification of suppliers takes place, causing prices to remain high, but lower than during the peaks of the energy crisis in 2022. A large share of Europe's gas is imported as LNG, which further drives prices up. Similarly, the import of coal is diversified, increasing coal prices as well. In 2030, a MWh of gas costs 50 2018€/MWh, a MWh of oil 70 2018€/MWh, and a MWh of coal 9 2018€/MWh ((Table 7). In 2045, those prices are 53, 77, and 8.5 2018€/MWh, respectively.

5.2.2.2. Low fossil fuel prices

Geopolitical détente and higher production leads to a relaxation of the markets. Some diversification takes place, causing increased energy security in Europe. With reliable and comparatively cheap supply, fossil fuel prices decrease accordingly and develop on a lower trajectory than in the high fossil fuel prices state. In 2030, a MWh of gas costs 25 2018€/MWh, a MWh of oil 46 2018€/MWh, and a MWh of coal 8.1 2018€/MWh (Table 7). In 2045, prices add up to 27, 52, and 7.7 2018€/MWh, respectively.

Table 7. The price trajectories for oil, coal, and gas in 2018-€. Source/Adopted from: [89].

	2025	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**
										Low fossil fuel import prices											
Gas (€/MWh)	46	42	38	34	29	25	25	25	25	25	26	26	26	26	26	26	26	26	26	26	27
Oil (€/MWh	40	42	43	44	45	46	47	47	47	48	48	48	49	49	49	50	50	50	51	51	51
[€/bbl])	(66)	(68)	(70)	(72)	(74)	(75)	(76)	(76)	(77)	(78)	(78)	(79)	(79)	(80)	(80)	(81)	(81)	(82)	(82)	(83)	(83)
Hard coal (€/MWh	13	12	11	10	9	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
[€/t])	(105)	(97)	(89)	(81)	(73)	(66)	(65)	(65)	(65)	(65)	(65)	(64)	(64)	(64)	(64)	(64)	(63)	(63)	(63)	(63)	(63)
										High fossil fuel import prices											
Gas (€/MWh)	77	72	66	61	56	50	50	51	51	51	51	51	52	52	52	52	52	53	53	53	53
Oil (€/MWh	63	64	65	67	68	69	70	70	71	71	72	72	73	73	74	74	75	75	76	76	77
[€/bbl])	(102)	(104)	(106)	(109)	(111)	(113)	(114)	(115)	(116)	(116)	(117)	(118)	(119)	(120)	(120)	(121)	(122)	(123)	(124)	(124)	(125)
Hard coal (€/MWh	17	15	14	12	10	9	9	9	9	9	9	9	9	9	9	9	9	9	9	8	8
[€/t])	(139)	(125)	(112)	(99)	(85)	(72)	(72)	(72)	(72)	(71)	(71)	(71)	(71)	(70)	(70)	(70)	(70)	(70)	(69)	(69)	(69)

5.2.3. Power-to-X (PtX) import prices

Regardless of their small-scale field of application today, Power-to-X (PtX, the conversion products of electricity to gases, fuels, liquids, and chemicals) will play a key role in the path to decarbonization [66]. Synthetic gas could generally be adopted as a substitute for natural gas, while synthetic fuels could replace fossil fuels in shipping, aviation, heavy transportation, and other areas where high energy density is required [90]. The role of hydrogen will be discussed in the descriptor *Hydrogen infrastructure*. Despite their potential, PtX prices could display a broad range: Much of the technological development still needs to take place. Furthermore, pricing could develop similarly to the market for natural gas today, where market prices are strongly decoupled from production costs [91]. Transportation costs could also constitute a significant part of (hydrogen) import prices. If import is possible via pipelines, they decrease [91]. All these factors make future price estimates challenging. Other factors of uncertainty include the availability of cheap production abroad (see Import potentials of PtX) as well as the worldwide demand for PtX products.

5.2.3.1. High import prices

High and low price trajectories are based on [92] and [93] on consultation with the (lead) author. Prices are given after transportation to Germany, and estimates for 2050 were moved forward to 2045. For 2030, prices of 174 €/MWh, 205 €/MWh, and 190 €/MWh are assumed for hydrogen, synthetic methane, and synthetic liquid fuels, respectively (Table 8). In 2045, these are 134 €/MWh, 155 €/MWh, and 138 €/MWh for hydrogen, synthetic methane, and synthetic liquid fuels, respectively.

5.2.3.2. Low import prices

Large-scale production, technological advancements and the absence of hydrogen cartels lead to low prices of PtX products. Price assumptions in 2030 are 137 €/MWh, 158 €/MWh, and 143 €/MWh for hydrogen, synthetic methane, and synthetic liquid fuels, respectively (Table 8). In 2045, they sink to 103 €/MWh, 116 €/MWh, and 99 €/MWh, for these three fuels, respectively.

Table 8. The import prices for hydrogen, synthetic methane and liquid fuels for 2030 and 2045 in the high and low import price scenario [92, 93].

Scenario (Year)	**Import price (€/MWh)**		
	Hydrogen	Synthetic methane	Liquid fuels
High (2030)	174	205	190
High (2045)	134	155	143
Low (2030)	137	158	143
Low (2045)	103	116	99

5.2.4. Import potentials of Power-to-X (PtX)

The conversion of electricity to gases, fuels, liquids, and chemicals, dubbed "Power-to-X" (PtX), is considered an essential part of the future energy system. As Germany's domestic production is not projected to be able to satisfy demand, imports become increasingly relevant [94]. However, it is uncertain how much PtX can theoretically be imported. Import potential essentially depends on three factors, which are also linked to each other: Supply in producing countries, demand within Germany, and a functioning import infrastructure.

For sufficient supply, the creation of a world market is beneficial. It requires three elements: technological development to reduce investment costs, sufficient and reliable demand, and investments in plants and infrastructure in PtX exporting countries [94]. In a second step, export agreements can be made with producing countries. For hydrogen, partnerships with countries such as Australia, Chile, Canada, Morocco, Namibia, Saudi Arabia, South Africa and the United Arab Emirates exist [95]. These partnerships could develop into reliable supply of hydrogen and other PtX products from these countries at a later stage. More and differing suppliers could also help to increase supply, albeit at the cost of higher import prices [95].

Another important factor is the import infrastructure in Germany, partly covered in the descriptor Hydrogen infrastructure. Import hubs at harbors and pipelines for geographically close producers can increase import capacities. In this regard, it is also important to have a consistent strategy within the EU: If Germany were to commit to the import of ammonia for hydrogen products, but its neighboring countries aimed for liquid hydrogen transportation, import potentials would decrease.

This descriptor describes states with a varying maximum possible import of PtX products. Thus, it does not define the number of imports, but only the potential amount of PtX products that could be imported. Specifically, the import potential for hydrogen, liquid fuels, and synthetic methane are varied. This way, representative PtX products are used to describe possible futures.

5.2.4.1. High import potentials

The world market for PtX products develops very dynamically. Various countries become exporters of PtX products, and Germany is able to conclude energy partnerships and import agreements with many of them. At the same time, the buildup of import infrastructure goes smoothly and is coordinated well with Germany's European partners. That way, import synergies are created and can be used. In 2045, the import potential for hydrogen, synthetic methane, and liquid fuels is 250 TWh, 200 TWh, and 200 TWh, respectively (Table 9).

5.2.4.2. Medium import potentials

The world market for PtX products develops smoothly and capacities are built up steadily. Import agreements are arranged with different countries, but less than in the previous state. Import infrastructure is built up at normal speed and is coordinated within the EU. In 2045, the import potential for hydrogen, synthetic methane, and liquid fuels is 200 TWh, 135 TWh, and 135 TWh, respectively (Table 9).

5.2.4.3. Low import potentials

The market for PtX products only builds up slowly. Supply from possible exporters is reduced, and Germany can only conclude very few import agreements. Within Germany, the import infrastructure is developing only gradually. In Europe, not all countries can agree on the same mode of import, leading to a fragmentation of the European market. In 2045, import potentials are 100 TWh, 30 TWh, and 30 TWh for hydrogen, synthetic methane, and liquid fuels, respectively (Table 9).

Table 9. Summary of import potentials for hydrogen, synthetic methane and liquid fuels in the different states. Sources: [69, 96].

Scenario	**Import potential (TWh/yr in 2045)**		
	Hydrogen	Synthetic methane	Liquid fuels
High	250	200	200
Medium	200	135	135
Low	100	30	30

5.2.5. Hydrogen infrastructure

Hydrogen will play a major role in the future German energy system. A meta study of five target scenarios estimates its demand at 400 to 650 TWh in 2045 [66]. Following the target scenarios, demand for hydrogen is spread over different areas of application: as feedstock or source of process heat for industry, for peak loads in power production – substituting natural gas in many instances, in transportation as potential fuel for ships, airplanes or heavy road transport, and possibly even to heat buildings [66, 97]. To achieve a quick market implementation for these applications, the German National Hydrogen Strategy (*Nationale Wasserstoffstrategie)* was developed [98]. In the current discussion, it is assumed that Germany will produce some of the hydrogen in the energy system of 2045. To do so, electrolysis capacities will have to be built within Germany. Mostly, however, hydrogen will have to be imported [66]. Developing the infrastructure for the import and distribution of hydrogen to its consumers in Germany requires both a national effort and a European collaboration, as outlined in the National Hydrogen Strategy. The most cost-efficient way to do so is through pipelines [99]. Natural gas pipelines can be refitted for hydrogen use, and new hydrogen pipelines will also have to be constructed. The timeline for developing the generation and distribution infrastructure is highly relevant: If investments are made too late, a lack of infrastructure prevents industries from switching fuel, thereby delaying the energy transition. If done timely, the infrastructure can foster the transition to hydrogen and can lead to a quicker reduction of natural gas consumption.

5.2.5.1. Timely expansion

The hydrogen infrastructure is built up quickly and follows the National Hydrogen Strategy [100, 101]. National and international production can be transported to the consumers. As a result, in 2030, first import pipelines connect industrial centers with the harbors in e.g., Rotterdam or Northern Germany [99]. By 2045, pipelines fully link Germany with neighboring countries, and provide a domestic network for production and consumption. National production develops according to the National Hydrogen Strategy: In 2030, there is a production capacity of 5 GW, which means that 14 TWh of hydrogen are produced at 4,000 full load hours and an efficiency of 70% [98]. By 2045, this number rises to 36 GW capacity and 100 TWh of hydrogen produced, assuming the same full load hours and efficiency as in 2030 [66]. Until 2030, large-scale geological storages for hydrogen are identified and become usable. Overall, this means that hydrogen is generally available for industry, provided that import and/or production capacities are not exceeded (see descriptor Import potentials of PtX).

5.2.5.2. Delayed expansion

Due to delayed construction, the expansion of infrastructure falls behind. Pipelines scheduled for 2030 are only available in 2040. German electrolysis capacity and hydrogen storage are also not scaling up quickly. By 2030, the national production capacity is 3.6 GW, and production reaches 10 TWh of hydrogen. By 2045, this is almost 18 GW and 50 TWh, respectively. Correspondingly, by 2045, the infrastructure for hydrogen transportation can only supply those industries where no alternatives to hydrogen exist. For most other applications in industry, power production, and other sectors, alternative, more expensive decarbonization strategies must be sought.

5.2.6. Power grid expansion

The German *Energiewende* necessitates a large-scale expansion of the German power grid. More variable renewable energy sources need to be integrated and balanced. Simultaneously, the decarbonization of all sectors leads to an increased demand for electricity. Despite efficiency improvements, overall electricity consumption will roughly double until 2045 [102]. Next to these challenges, the imbalance between southern consumption and northern production areas is increasing. Nuclear power plants, which had provided electricity to large industrial and population centers in the south, are being phased out. At the same time, onshore and offshore wind, which will be generating a bulk of Germany's electricity, are overwhelmingly being installed in the north [66]. All these developments require a larger, more robust grid: According to the bi-yearly grid development plan (*Netzentwicklungsplan*, NEP), 11,600 to 12,800 km of grid connections will have to be strengthened or renewed until 2035 [103]. Yet, grid development so far has fallen short of expectations. "Suedlink" (Southern Link) and "SuedOstLink" (South-Eastern Link), the two most important projects to transport wind-generated electricity from the north to the south, have been repeatedly pushed back. Suedlink, planned to be finished by 2022, is now scheduled for 2028. SuedOstLink currently aims for 2027 instead of 2025 [104]. The German grid operators and the grid agency consider even those targets "very ambitious" or "questionable" [104]. Two reasons are seen as the main cause for setbacks like these. Firstly, long approval procedures cause significant delay [104]. Secondly, local politics and initiatives often oppose projects, trying to slow down and obstruct construction of overhead lines [105]. For instance, this led to a switch from overhead to underground cables in Suedlink, causing part of the project's delay [104].

5.2.6.1. Grid expansion as currently planned

The schedule outlined in the NEP is followed as currently intended, including a delivery of Suedlink, SuedOstLink and other major projects without further delay. Through doing so, the grid can provide large industrial centers with sufficient electricity, allowing electrification where needed. A number of developments make this possible: As intended in the most recent coalition agreement, the duration of approval procedures is halved [75]. This is achieved through a simplification of administrative procedures and an increase in personal and technical capacities in public authorities and courts [75]. Furthermore, growing participation in the planning process boosts public acceptance and reduces local resistance to grid projects [105]. As a result, grid expansion keeps up with the increasing demand for electricity until 2045.

5.2.6.2. Delayed grid expansion

The expansion of the grid continues at a similar pace as during the last ten years. It sees further delays and is unable to follow the NEP. On average, new connections are delivered five years behind schedule. Major projects are pushed back further, leading to deliveries of Suedlink in 2033 and Suedostlink in 2032 (a five-year delay compared to current plans). The grid is overloaded with the increasing demand and production: Due to these capacity problems, new wind and solar parks are frequently connected to the grid later than intended. For consumers, this leads to less availability of renewably produced electricity.

5.2.7. Market entry of industrial decarbonization technologies

The central role of technology to the decarbonization of industry and hence, society, is undisputed. A slow technological development can seriously endanger the German climate goals. It could also make a transition to climate neutrality much more costly. Until 2030, more than 50% of the steel and chemical industry production capacities and 30% of the cement industry production capacities need to be reinvested and/or substituted [10]. If technologies for the decarbonization of these industries are not available, costs increase, as more equipment requires will be substituted then and again a few years later, when the technologies are available. On the other hand, an early market entry of carbon-neutral technologies would avoid costs and save emissions.

However, the techno-economic development of technologies is not usually predictable. Scientific difficulties can slow down development, while favorable environments or non-monetary incentives could stipulate it. For instance, nuclear fusion has long been thought to solve most of humanity's energy needs [106]. Yet, it is still to leave the research and development phase. In contrast, solar PV has systematically been underestimated and has fallen in costs much faster than predicted [107].

Here, the market entry of industrial decarbonization technologies is defined as the earliest possible application of six key technologies. These technologies are hydrogen direct reduction iron making (H2-DRI), methanol-to-olefins (MTO) and methanol-to-aromatics (MTA) processes in the chemical industry, CO_2 capturing through oxyfuels in the cement industry, and power-to-heat (PtH) through high temperature heat pumps (HTHPs) and through electrode boilers in the entire industry. The earliest possible application does not mean that a technology is introduced on large scale immediately, but rather that technologies are adopted for the first time in an industrial site. Thus, they have reached a technological readiness level (TRL) of 9. A gradual rollout would then follow in the years after.

5.2.7.1. Quick market entry

This state describes exceptionally swift technological advances. For all key technologies, projects run ahead of schedule. National and international projects are quickly conducted, learned from and repeated in other industrial sites in Germany. H2-DRI, MTA, MTO, and CO2 capturing through oxyfuels are all introduced from 2025 onwards. The PtH technologies are even available first in 2023 (Table 10).

5.2.7.2. Medium-fast market entry

Here, the market entry of the six key technologies runs smooth, even though advancements are not as impressive as in the previous state. Most technologies are first introduced in Germany by 2030. The exceptions are PtH applications, which become available from 2023 (electrode boiler) and 2025 (HTHP) onwards, respectively (Table 10).

5.2.7.3. Slow market entry

A mix of technological setbacks, a lack of funding, and other obstructions causes significant delay in the development of the key technologies. The market entry of electrode boilers and HTHPs are in 2025 and 2030, respectively. All other technologies are only introduced from 2035 onwards. As a result, the decarbonization of the industry becomes substantially delayed, leading to the need for enormous efforts between 2035 and 2045 to still reach carbon neutrality in time (Table 10).

Table 10. The different assumed market entry date of key decarbonization technologies.

Sector	**Technology**	**TRL in 2019 [10]**	**Market entry**		
			Slow	**Medium**	**Fast**
Iron and steel	Hydrogen direct reduction iron making	4-5	2035	2030	2025
Chemical industry	Methanol-to-olefins	8	2035	2030	2025
Chemical industry	Methanol-to-aromatics	6	2035	2030	2025
Cement industry	CO_2 capturing through oxyfuels	6	2035	2030	2025
Cross-sector	Power-to-heat: Electrode boiler (up to 500 °C)	8-9	2025	2023	2023
Cross-sector	Power-to-heat: High temperature heat pump (above 150 °C)	5-7 [108]	2030	2025	2023

5.2.8. Circular economy and digitalization

Although the "circular economy" as an idea is not new, it has risen to renewed popularity in recent years [68]. Some even see it as a key measure to mitigate climate change [109]. The concept revolves around the reduction of the extraction and processing of new resources to a minimum. This is achieved through recycling of materials, higher material efficiency, and material substitution [110]. More specifically, this means a higher share of recycling, reducing waste, new structures that save materials, substitution of carbon-intensive materials with more sustainable solutions, extending the lifetimes of products and an intensification of use [109]. In some cases, new business models and services could emerge. These could make previous products and value chains obsolete. Through all these measures, the use of carbon-intensive commodities like steel, cement, aluminum and plastics could be reduced [109].

Recently, more links have been laid between the circular economy and the digitalization. [111, 112]. The digitalization involves the "virtualization of products and processes," the interconnection of machines and humans with themselves and among each other, and the sharing of data within such a system [113]. Examples include online platforms and applications that lower transaction costs [111]. In supply chains, the digitalization facilitates the exchange of data. That way, they become more flexible and saving potentials are easier identifiable [111]. Smart sensors in the industry can collect data on system performance, thereby enabling an optimization of industrial processes [114].

With the implementation of these technologies and the transition to fewer and more sustainable materials, the same services as before are provided. This constitutes a difference to the demand changes illustrated in the descriptor Societal trends, which affect production output. Yet, also here, an effect on production output is evident: If resources are used more efficiently, fewer materials are needed overall.

5.2.8.1. Circular economy expanding

This state is characterized by an expansion of the circular economy. Recycling rates of energy-intensive commodities and others increase significantly (Table 11). Furthermore, materials are partly substituted, and new designs lead to a lower consumption of materials. The advancing digitalization leads to further synergy effects and reductions in the use of materials, as information can be exchanged more easily, and production becomes more efficient. With these changes, the production of materials can be reduced (Table 12).

Table 11. Change in recycling of key energy-intensive commodities in the circular economy. Source: [68].

Product	Recycling rates in 2045
Steel	60% recycled steel used (today: 30%)
Plastics	15 percentage points increase in recycling (mechanical and chemical)
Paper	85% recycling rate (today: 77%)
Aluminum	80% recycled aluminum used (today: 54%)

Table 12. Improvements in material efficiency in the "circular economy expanding" state. These improvements are potential reductions embedded in the system and are therefore uncertain. Source: [68].

Product	Decrease in production (2045) compared to reference	Explanation
Crude steel	10%	More efficient use of steel and material substitution
Aluminum	<5%	Decrease in demand
Paper	10%	Trend to paperless applications (digitalization)
Container glass	15%	Efficient use of materials
Cement	15%	Material efficiency in the construction sector
Cement clinker	37%	Substitution with other materials
Lime	30% [1]	Strong decrease through phase-out of coal-fired power generation and through switch from blast furnace to other steel production
Ammonia	20%	More efficient fertilizing techniques
Plastics	15%	Decrease in use, e.g., packaging material

[1] Value adjusted after consultation with author.

5.2.8.2. Business-as-usual (BAU)

This state describes a world where the circular economy does not achieve such a prominent role. Recycling rates are improved, but the gains remain modest (Table 13). Similarly, material efficiency does not make the same gains as in the state "Circular economy expanding" (Table 14). The digitalization remains an important development. Yet, it does not develop as disruptive as seen in the previous state.

Table 13. Change in recycling of key, energy-intensive commodities in the BAU state.

Product	Recycling rates in 2045
Steel	35% recycled steel used (today: 30%) [11]
Paper	80% recycling of old paper (today: 77%)
Aluminum	62% recycled aluminum used (today: 54%) [11]

Table 14. Improvements in material efficiency in the BAU state. Efficiency gains between <5 (aluminum) and 10 percentage points lower than in [68].

Product	Decrease in production (2045) compared to reference	Explanation
Crude steel	0%	Constant steel demand [11]
Aluminum	0%	No change
Paper	0%	No change
Container glass	5%	Slightly more efficient use of materials
Cement	5%	Slightly improved material efficiency in the construction business
Cement clinker	27%	Substitution through other materials
Lime	10%	Decrease through phase-out of coal-fired power generation and through switch from blast furnace to other steel production

Table 14. *(cont.)*

Ammonia	10%	Somewhat efficient fertilizing techniques
Plastics	5%	Slight decrease in use, e.g., packaging material

5.2.9. Corporate strategies

In recent years, more and more companies have realized the need to take climate action [115]. When doing so, companies can be a driver of positive change, innovating new, sustainable technologies and accelerating the transition to a carbon-free economy [116]. On the other hand, some companies show a lagging response and a reliance on government targets and regulations. Depending on which companies are more prevalent, their ambitions can slow down progress or advance change.

5.2.9.1. Ambitious corporate strategies

In this state, many companies, independent of size and energy intensity, apply corporate sustainability targets. To describe their target, they use terms and definitions of the IPCC and have absolute and clear reduction targets [117]. Some companies take on a pioneering role and encourage others to take climate actions with their innovative strength. When new technologies become available, which help reduce their carbon footprint, most companies implement them readily. By applying these standards, companies become agenda setters who can credibly push for climate legislation.

5.2.9.2. Moderately ambitious corporate strategies

This state describes a moderately ambitious corporate environment. While almost all large companies apply corporate sustainability targets, only some small and medium-sized enterprises (SMEs, staff headcount smaller than 250 [118]) do so. Reporting does not always follow best practice and timelines are given occasionally. While some companies play an active role to reach climate neutrality, others slow down the transition and try to hold on to their old business models for as long as possible. Generally, there is less innovative strength in companies than in the previous state. New technologies are utilized, but not always immediately, and financial considerations limit the willingness to do so.

5.2.9.3. Unambitious corporate strategies

This state is characterized by a small number of companies using corporate sustainability targets. Ambitions are generally low, and most, if not all change must be induced externally, i.e., through regulations. While some, mostly large companies apply corporate sustainability targets, SMEs do not tend to pick up on these goals. For those companies, reporting is only done sporadically, and does not exceed the required coverage. Often, inconsistent standards and definitions of climate neutrality are used. Due to overall lower ambitions, new technologies are implemented later or through regulations and legislation.

5.2.10. Relocation of industry

The migration of German industry to production centers abroad has been a point of discussion for decades (compare, e.g., [119]). The current energy crisis and the intention to decarbonize the industry have refueled the topic. Specifically, energy-intensive industries seem the most likely to relocate, if policy measures (see descriptor Climate Policies) cannot provide a level playing field between imports and goods produced in Germany. Here, the cement industry is the exception: It seems less to relocate, as cement is - due to its low specific value (by mass) - barely traded internationally, unless highly efficient modes of transportation (e.g., shipping) can reach both supply and demand centers. The challenges of other industries differ, but are often related to the availability and costs of fossil and renewable resources. Among those potentially relocating, the ammonia production industry and, to a lesser extent, the iron and steel industry stand out. They will be used as case studies here.

The European iron and steel industry is vulnerable to volatile or high prices, uncertainties around climate change policies, and market shocks [120]. Furthermore, a shift towards direct reduction iron making (DRI) seems plausible, as DRI can be carried out with green hydrogen [121]. Currently, DRI is mostly used in countries outside Europe [122]. Ammonia's case is strongly connected to hydrogen, which is needed for the decarbonization of society. Hydrogen itself is expected to be imported, and ammonia is easy to ship [11]. Therefore, ammonia production in Germany will likely decrease. Additionally, current production routes via natural gas also show sensitivity to prices in Europe. An example of this sensitivity was observed only recently: Due to high natural gas prices, in September 2021, ammonia production fell by 40%, with the production gap made up for by imports 2-3 months later [123]. With long-term higher natural gas prices, production seems likely to shift.

5.2.10.1. Widespread relocation

An exodus takes place in the energy-intensive industry. Until 2030, a third of German iron demand is satisfied by sponge iron, the product of DRI. The sponge iron is produced and traded internationally. After 2030, a quarter of the remaining German raw iron production ceases as well. This means that in 2045, 50% of the current industrial demand for iron is satisfied by imported sponge iron, rather than raw iron produced in Germany. The ammonia industry largely ceases production in Germany until 2030, with only few, insignificant factories remaining after. Other industries migrate too, albeit on a smaller scale: Some companies of the manufacturing industry move their production abroad.

5.2.10.2. Moderate relocation

Moderate relocation occurs in Germany's energy-intensive industry. A sixth of current production of raw iron is substituted by internationally produced sponge iron by 2030. After 2030, German iron production remains stable, although production routes are altered, as the sector becomes carbon-neutral. In the ammonia sector, half of all production relocates until 2030. The sector continues to shrink after 2030, with about 25% of current production remaining in 2045. Other industries remain relatively stable, with only few factories being moved abroad.

5.2.10.3. Minor relocation

Barely any relocation occurs. Both the iron and steel and manufacturing industries continue to be stable. Some of the ammonia production migrates, but after 2030, the sector remains stable at 70% of current production rates.

5.2.11. Negative Emissions and residual emissions

Some emissions, particularly in agriculture and in industrial processes (cement and lime production) cannot be curbed [70]. These "residual emissions" necessitate the use of negative emissions. Negative emissions include a whole range of technological, biological, and geological solutions to sequester CO_2 from the atmosphere and use or store it permanently. Thus, with negative emissions, CO_2 is removed from the carbon cycle.

The most commonly mentioned alternatives are bio-energy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), and the utilization of forests and other nature as natural carbon sinks. BECCS technologies make use of carbon stored in biomass, which is then burned, and mostly captured with different technologies. They could be most useful in district heating plants, and in high temperature process heat in the steel or chemical industry [11]. However, its capacity is limited by the potential for biomass in Germany. DACCS does not operate with point sources, but rather filters CO_2 from the ambient air. This requires significant amounts of energy [69]. At the same time, DACCS is only limited indirectly by the availability of renewably produced electricity. Both technologies have mostly remained in a testing phase so far [69]. Furthermore, both BECCS and DACCS rely on a national infrastructure to not only capture the CO_2, but to transport and store or use it safely. Especially, the storage of CO_2 in geological structures or old gas fields is a potential source of conflict with local populations [69]. CO_2 could also be used as a feedstock in other processes. This could make the capturing process more economically viable and could be an efficient method of utilizing the CO_2, without having to store it in the ground [124]. Options include using CO_2 in fuels like green methanol or green naphtha. However, in that case, the CO_2 is released back into the atmosphere. "True" negative emissions, as considered here, remove the CO_2 from the cycle and bind it permanently. For instance, this occurs when CO_2 is utilized in building materials [124].

Next to these paths, also different options, albeit with less emission mitigation potential, exist: Enhanced weathering, soil enrichment with carbon, plant coal, or rewetting of peatlands, to name but a few [69]. Together with the use of forests as carbon sinks, these fall under the term land use, land-use change and forestry (LULUCF). Different studies assume varying potentials for negative emissions from LULUCF [66]. Here, we assume 11 Mt-CO_2-eq from LULUCF in 2045 [70]. The two states then depict a path with more and less negative emissions from BECCS and DACCS, respectively. Depending on these, varying amounts of remaining emissions could be possible in other sectors, while still reaching climate neutrality until 2045.

5.2.11.1. Low residual emissions and limited use of negative emission technologies

Negative emission technologies are only adopted and promoted slowly. Skepticism of CO_2 storage in gas fields or geological structures remains and becomes stronger. Therefore, focus is put on decarbonizing other sectors as much as possible, and only using negative emissions as a last resort. Following [66], a strong reduction of residual emissions to 49 Mt-CO_2-eq in 2045 is assumed. In such a case, CCS is used for all industrial processes that cannot be decarbonized, the number of livestock is strongly reduced, fertilizer is used more efficiently, and waste management is improved [66]. 38 of the 49 Mt-CO_2-eq of residual emissions have to be mitigated through BECCS and DACCS. From 2030 onwards, this capacity is slowly built up and is reached in 2045.

5.2.11.2. High residual emissions and extensive use of negative emission technologies

Negative emission technologies are adopted readily and quickly develop into an important mitigation option. Technologies like carbon storage in gas fields do not meet significant resistance by the population. From 2030, the technologies are employed, first BECCS, then DACCS as well. This means that in 2045, 57 Mt-CO_2-eq are removed with BECCS and DACCS, and then stored or utilized, while 11 Mt-CO_2-eq are stored in natural sinks through LULUCF [70]. That way, 19 Mt-CO_2-eq more than in the other state can be emitted. For example, the reduction of animal livestock could be less extreme [69].

5.2.12. Societal trends

Societal trends summarize multiple societal developments in one descriptor. They cover a spectrum ranging from a broad movement of people willing to adjust their lifestyle to one that is more environmentally friendly to no inclination to do so, depending on the society's awareness of planetary boundaries and climate change. These trends in turn affect demand within Germany. Despite being an export-oriented economy, national demand plays a major role for industrial production too. On the short-term, demand changes are usually linked with the economic situation. On the long-term, however, different factors play a role. For example, there is a movement toward individualization, which manifests itself in a trend to live alone. This in turn increases the per capita consumption of space. Since 1990, average living area per capita has grown by 37% [125]. As a result, more living space is needed, increasing domestic demand for cement and steel.

At the same time, mobility is increasing. Before the Covid-19 pandemic led to a sharp decline in traveling, numbers had risen continuously. Between 2000 and 2019, the number of air passengers in German airports almost doubled [126]. In the same period, the average distance traveled in Germany increased by 12% [126]. It is yet to be seen whether the pandemic has had a lasting impact on mobility patterns.

Finally, societal trends affect the demand for consumer goods, potentially causing an increase or decrease in production volumes. The "sharing economy" could lead to a reduction in ownership and a growth in shared commodities, e.g., cars [127]. Consequentially, demand for cars would sink. An increased repair-and-recycle mentality could have the same effect on other goods. However, it is noteworthy that other trends point in the opposite direction. For instance, gains in efficiency of data centers have so far been offset by the growth of internet traffic and demand [128]. A trend towards driving larger vehicles has negated improvements in fuel efficiency [129]. For the future, both an upward and a downward development in demand seem possible.

5.2.12.1. Increasing consumption

This state describes a business-as-usual (BAU) scenario. Rather than reducing society's footprint, current trends leading to higher consumption continue, and new trends become relevant that reinforce this development. Individual living area continues to increase, and so do distances traveled. Overall, societal trends are characterized by increasing demand. Thus, behavioral changes occur, but point towards more consumption, rather than less.

5.2.12.2. Constant development

In this state, neither a strong move towards sustainability nor an increase of consumption takes place. Instead, current levels for living area, mobility, and consumption remain constant. Given that all these factors have increased in the past, this represents an improvement to the BAU state.

5.2.12.3. Sufficiency behavior

This state describes a world where society widely adopts more sustainable ways of living. Current sustainable trends are strengthened, while more unsustainable developments diminish. People also use their resources more sustainably: devices are used longer and are more often repaired. As the sharing economy gains popularity, the consumption of goods and services decreases. Generally, a large share of the population voluntarily reduces individual consumption.

5.3. Cross-impact matrix (CIM) and influences

Based on these essays, experts evaluated the impact of the different states upon each other by assigning them a value between -3 and +3. Thereby, they answered RQ3.[9] As there are 822 individual assessments, examples are used to describe the relationships between the descriptors. Together, these individual assessments make up the CIM. The entire matrix can be seen in Table 15.

Looking at descriptor 9, "corporate strategies," it is clear that it has a significant influence on descriptor 1, "climate policies." With (moderately) ambitious corporate strategies, ambitious climate policies become easier to implement. In contrast, when corporate strategies are unambitious, they also promote unambitious climate policies. Looking at the influence of climate policies on corporate strategies, it can be seen that the relationship goes both ways: (Very) ambitious climate policies make ambitious corporate strategies more likely, while

[9] RQ3: What is the impact of [the factors affecting the decarbonization of the German industry] upon each other?

unambitious climate policies are more likely to lead to unambitious corporate strategies as well.

It can also be seen, for example, that the experts found no impact of corporate strategies on fossil fuel prices (descriptor 2). As they are traded on the world market, they found Germany's impact too small to influence prices. A small influence was found when visioning the impact of an expanding circular economy (state 8a) on hydrogen infrastructure (descriptor 5). With higher recycling rates, fewer hydrogen is needed for steel production, slightly reducing the need for a timely expansion of hydrogen infrastructure and capacities for steel production in Germany.

Lastly, a descriptor with considerable influence is "societal trends" (descriptor 12). For example, "increasing consumption" is one of the key drivers of high residual emissions and therefore, also of an extensive use of negative emission technologies (state 11b). On the other hand, sufficiency behavior has a strongly promoting influence on low residual emissions and a limited use of negative emission technologies.

Following from the matrix, the active-passive sums can be calculated, as discussed in chapter 4.5. The sums are displayed in an active-passive diagram (Figure 4). The figure makes direct influences more obvious. From it, it is apparent that there is a wide range in the size of direct influences. The descriptors "climate policies," "PtX import prices," and "hydrogen infrastructure" hold the highest active sum, i.e., they exert the most direct influence on other descriptors. Then, there is a cluster of "fossil fuel prices," "import potentials of PtX" and "societal trends," which are also strongly influencing other descriptors. "Market entry of industrial decarbonization technologies," "corporate strategies," "relocation of industry" and "negative emissions and residual emissions" have an average influence on other descriptors. In comparison, "power grid expansion" has by far the lowest influence, followed by "circular economy and digitalization."

In terms of passive sums, i.e., the number of other influences on a descriptor, "relocation of industry" and "hydrogen infrastructure" have the highest value. This means that the development in these descriptors is highly dependent on other factors. They are followed by the "market entry of industrial decarbonization technologies" and "corporate strategies," which both are highly influenceable as well. "Negative emissions and residual emissions" and "PtX import prices" also display an above-average passive sum. The influence upon "fossil fuel prices," "import potentials of PtX," "circular economy and digitalization" and "societal trends" is mediocre. The smallest influence is exerted upon "climate policies," followed by "power grid expansion." Thus, the influence of corporate strategies upon climate policies discussed above is one of the few significant impacts upon this descriptor.

Overall, this indicates that "climate policies" is a strongly influential factor for the realization of climate neutrality, which is also barely swayed by other descriptors. For example, "hydrogen infrastructure" is similarly influential, but also strongly dependent upon other factors. "Power grid expansion" interacts the least with other descriptors, followed by “circular economy and digitalization:” Both their active and passive sums are comparatively low.

Table 15. The cross-impact matrix as filled in by the consulted expert groups. Influences are coded as follows: -3: strongly restricting influence, -2: moderately restricting influence, -1: weakly restricting influence, 0: no influence, +1: weakly promoting influence, +2: moderately promoting influence, +3: strongly promoting influence [54]. Influence direction is from the horizontal (left-hand) side to the vertical side (1a, 1b, 1c, 2a, …). The dashed outlines indicate evaluation fields discussed in the text.

	1			2		3		4			5		6		7			8		9			10			11		12		
	1a	1b	1c	2a	2b	3a	3b	4a	4b	4c	5a	5b	6a	6b	7a	7b	7c	8a	8b	9a	9b	9c	10a	10b	10c	11a	11b	12a	12b	12c
1. Climate policies																														
1a Very ambitious climate policies				-1	1	0	0	1	1	-1	2	-2	1	0	3	1	-1	3	-1	2	0	-2	-2	1	2	2	-1	-2	-1	2
1b Ambitious climate policies				0	0	0	0	1	1	-1	2	-2	2	-1	3	2	-1	1	0	2	0	-2	-2	1	2	0	1	0	0	0
1c Unambitious climate policies				1	-1	0	0	-1	0	1	-2	2	-2	1	-1	0	1	-2	2	-2	0	2	1	0	-1	0	0	2	-1	-2
2. Fossil fuel prices																														
2a High fossil fuel prices	0	0	0			3	-3	3	2	1	2	1	0	0	1	1	0	1	0	1	1	-1	3	2	2	1	0	-1	1	1
2b Low fossil fuel prices	0	0	0			0	3	0	0	0	0	0	0	0	-1	0	0	0	0	-1	1	1	-3	-2	3	0	3	1	0	-1
3. Power-to-X (PtX) import prices																														
3a High PtX import prices	0	0	0	1	-1			1	0	-1	-2	2	0	0	-3	-1	3	0	0	-2	-1	1	3	2	-1	-2	2	-2	1	2
3b Low PtX import prices	0	0	0	1	-1			-1	0	1	2	-2	0	0	3	1	-3	0	0	2	1	-1	-1	0	3	2	-2	2	1	-2
4. Import potentials of PtX																														
4a High import potentials	0	1	-1	-2	2	-2	2				2	-2	-1	1	2	1	-2	-1	1	1	0	-1	-2	-1	2	0	0	0	0	0
4b Medium import potentials	0	0	0	-1	1	-1	1				1	-1	0	0	1	0	-1	0	0	0	0	0	-1	0	1	0	0	0	0	0
4c Low import potentials	0	-1	1	2	-2	2	-2				-2	2	1	-1	-2	-1	2	1	-1	-1	0	1	2	1	-2	0	0	0	0	0
5. Hydrogen infrastructure																														
5a Timely Expansion	0	0	0	-2	2	-2	2	3	1	-1			-1	1	2	1	-2	-1	1	2	1	0	-2	-1	0	0	0	1	1	-1
5b Delayed Expansion	0	0	0	0	0	-2	2	-3	-2	3			1	-1	-2	-1	2	1	-1	-1	-1	0	2	1	0	0	0	-1	-1	1
6. Power grid expansion																														
6a Grid expansion as planned	0	0	0	0	0	0	0	1	1	0	0	1			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6b Delayed grid expansion	0	0	0	0	0	0	0	2	1	0	1	0			0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0
7. Market entry of industrial decarbonization technologies																														
7a Quick market entry	1	1	0	0	0	1	-1	0	0	0	0	0	2	-2				-1	1	3	2	0	-3	-1	0	0	0	0	0	0
7b Medium-fast market entry	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0	0	0	0	1	-1	0	0	0	0	0	0	0
7c Slow market entry	-2	-2	1	0	0	0	0	0	0	0	0	0	-1	1				1	-1	-2	-1	2	3	1	0	0	0	0	0	0
8. Circular economy and digitalization																														
8a Circular economy	0	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0			1	0	-1	-2	-1	0	2	-2	-1	0	1
8b Business-as-usual (BAU)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			-1	0	1	1	0	0	-1	1	0	0	-1
9. Corporate strategies																														
9a Ambitious corporate strategies	2	2	0	0	0	0	0	0	0	0	1	-1	0	0	2	0	-1	2	-1				0	0	0	2	-2	-1	0	2
9b Moderately ambitious corporate strategies	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0				0	0	0	0	0	0	0	0
9c Unambitious corporate strategies	-1	0	2	0	0	0	0	0	0	0	-1	1	0	0	-1	0	2	-1	2				0	0	0	-2	2	2	0	-1
10. Relocation of industry																														
10a Widespread relocation	-2	0	1	0	0	0	0	0	0	0	-2	2	-1	1	-2	0	1	1	-1	-2	0	1				1	-1	-1	-1	1
10b Moderate relocation	-1	0	0	0	0	0	0	0	0	0	-1	1	0	0	-1	0	0	1	-1	-1	0	0				0	0	-1	0	0
10c Minor relocation	2	1	0	0	0	0	0	0	0	0	1	-1	0	0	1	0	-1	0	0	2	1	0				0	0	0	0	-1
11. Negative emissions and residual emissions																														
11a Low residual emissions and limited use of negative emission technologies	0	0	0	-1	1	1	-1	0	0	0	0	0	-1	1	1	0	-1	0	0	-2	-1	1	1	0	-1			-1	0	0
11b High residual emissions and extensive use of negative emission technologies	0	0	0	1	-1	-1	1	0	0	0	0	0	1	-1	-1	0	1	0	0	2	1	-1	-1	0	1			1	0	0
12. Societal trends																														
12a Increasing consumption	-2	-1	1	2	-1	1	-1	3	2	-1	3	-1	0	0	1	0	0	0	1	0	0	1	-1	0	1	-2	3			
12b Constant development	-1	0	0	1	0	1	-1	2	1	0	2	0	0	0	1	0	0	1	0	1	2	0	0	0	0	0	1			
12c Sufficiency behavior	3	2	-2	-1	1	-1	0	-2	-1	1	-1	1	1	0	2	1	0	3	0	2	1	-1	1	0	0	3	-2			

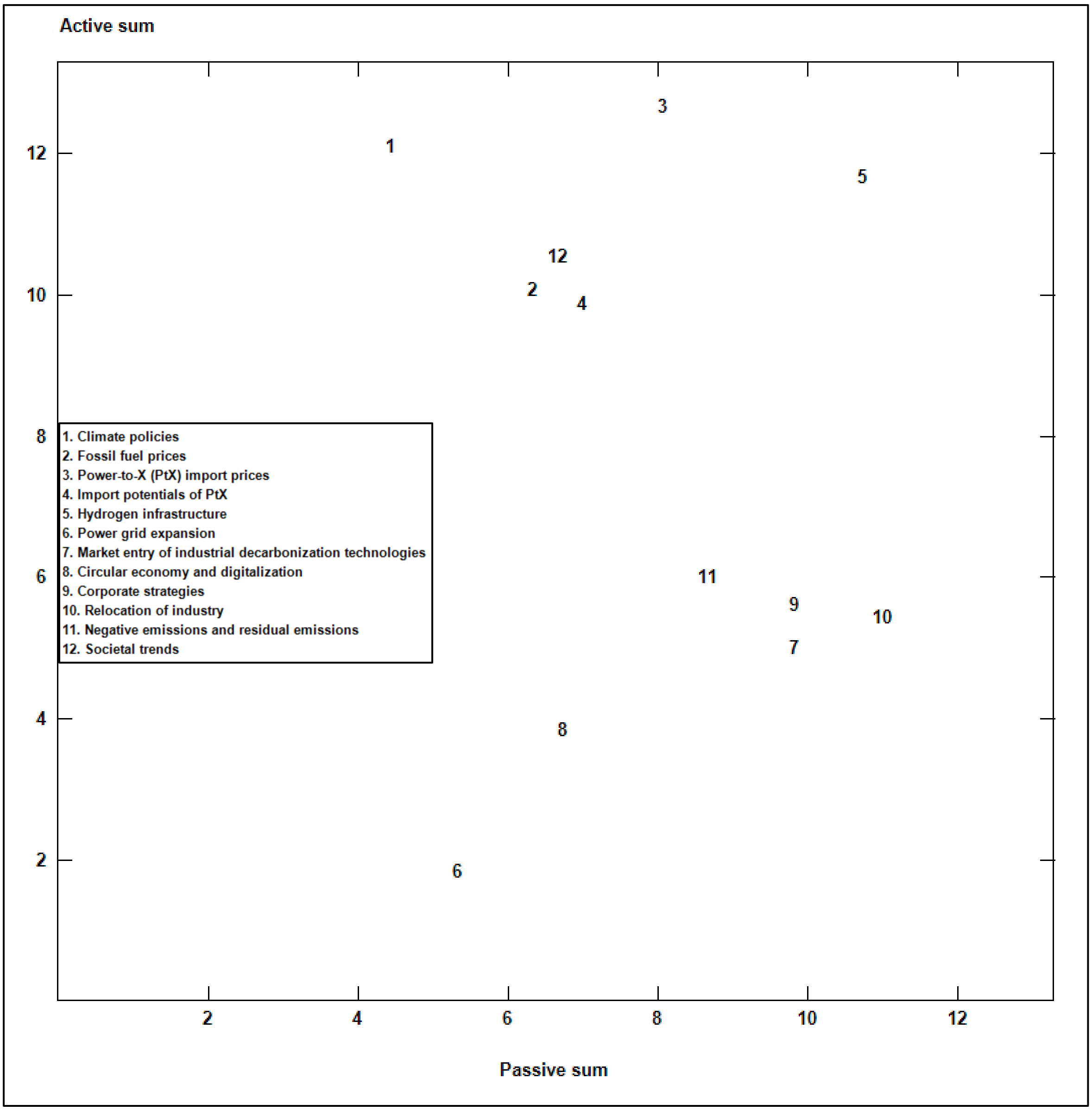

Figure 4. The active-passive diagram of the cross-impact matrix [55].

5.4. Scenarios

5.4.1. Overview of consistent scenarios

After running ScenarioWizard's identification program of consistent scenarios, 16 consistent scenarios remained (Table 16, RQ4[10]). Three of them were perfectly internally consistent (scenarios 6, 11, and 13), and 13 scenarios had a maximum inconsistency level of 1, as described in the Method section. Partially, the scenarios display major differences. However, it is also apparent that some states are highly dominant.

For example, for the descriptors "PtX import prices," "hydrogen infrastructure," "market entry of industrial decarbonization technologies," "corporate strategies," and "relocation of industry," 14 out of 16 scenarios selected the states "low PtX import prices," "timely

[10] RQ4: Which consistent scenarios of decarbonizing the German industry until 2045 are possible?

expansion," "quick market entry," "ambitious corporate strategies," and "minor relocation," respectively. For descriptors "fossil fuel prices" and "import potentials of PtX," 13 scenarios chose "low fossil fuel prices" and "high import potentials," respectively. At the same time, a medium-fast market entry of industrial decarbonization technologies, moderately ambitious corporate strategies, and a moderate relocation of industry are states not represented in any consistent scenarios. Appendix F presents a table with the exact distributions.

From these 16 scenarios, four were selected to depict the different possible futures, based on the selection technique outlined in chapter 4.5, to answer RQ5.[11] These were scenarios 3, 4, 12, and 15 (Table 16). After selection, they were named "Slow and delayed change hinders the energy transition" ("Delay," scenario 3), "Heavy reliance on PtX" ("PtX," scenario 4), "Rapid scale-up of decarbonization technologies" ("Rapid scale-up," scenario 12), and "Societal change," (scenario 15). The storylines of these scenarios are presented in the next section.

[11] RQ5: Which scenarios can be chosen to depict different possible futures?

Table 16. The three fully consistent scenarios (scenarios 6,11, and 13), as well as the 13 scenarios with an inconsistency value of 1, as calculated with ScenarioWizard. The scenarios selected to depict the different possible futures are scenarios 3, 4, 12, and 15.

<table>
<tr><th>Scenario No. 13</th><th>Scenario No. 3</th><th>Scenario No. 4</th><th>Scenario No. 6</th><th>Scenario No. 5</th><th>Scenario No. 1</th><th>Scenario No. 11</th><th>Scenario No. 8</th><th>Scenario No. 10</th><th>Scenario No. 7</th><th>Scenario No. 9</th><th>Scenario No. 12</th><th>Scenario No. 2</th><th>Scenario No. 16</th><th>Scenario No. 14</th><th>Scenario No. 15</th></tr>
<tr><td colspan="2">1. Climate policies: 1c Unambitious climate policies</td><td colspan="2">1. Climate policies: 1b Ambitious climate policies</td><td colspan="2">1. Climate policies: 1a Very ambitious climate policies</td><td colspan="3">1. Climate policies: 1b Ambitious climate policies</td><td colspan="2">1. Climate policies: 1a Very ambitious climate policies</td><td>1. Climate policies: 1b Ambitious climate policies</td><td colspan="4">1. Climate policies: 1a Very ambitious climate policies</td></tr>
<tr><td colspan="3">2. Fossil fuel prices: 2a High fossil fuel prices</td><td colspan="13">2. Fossil fuel prices: 2b Low fossil fuel prices</td></tr>
<tr><td colspan="2">3. Power-to-X (PtX) import prices: 3a High PtX import prices</td><td colspan="14">3. Power-to-X (PtX) import prices: 3b Low PtX import prices</td></tr>
<tr><td colspan="2">4. Import potentials of PtX: 4c Low import potentials</td><td colspan="13">4. Import potentials of PtX: 4a High import potentials</td><td>4. Import potentials of PtX: 4b Medium import potentials</td></tr>
<tr><td colspan="2">5. Hydrogen infrastructure: 5b Delayed Expansion</td><td colspan="14">5. Hydrogen infrastructure: 5a Timely Expansion</td></tr>
<tr><td>6. Power grid expansion: 6b Delayed grid expansion</td><td colspan="7">6. Power grid expansion: 6a Grid expansion as planned</td><td>6. Power grid expansion: 6b Delayed grid expansion</td><td>6. Power grid expansion: 6a Grid expansion as planned</td><td colspan="4">6. Power grid expansion: 6b Delayed grid expansion</td><td colspan="2">6. Power grid expansion: 6a Grid expansion as planned</td></tr>
<tr><td colspan="2">7. Market entry of industrial decarbonization technologies: 7c Slow market entry</td><td colspan="14">7. Market entry of industrial decarbonization technologies: 7a Quick market entry</td></tr>
<tr><td>8. Circular economy and digitalization: 8a Circular economy</td><td colspan="6">8. Circular economy and digitalization: 8b Business-as-usual (BAU)</td><td colspan="4">8. Circular economy and digitalization: 8a Circular economy</td><td colspan="2">8. Circular economy and digitalization: 8b Business-as-usual (BAU)</td><td colspan="3">8. Circular economy and digitalization: 8a Circular economy</td></tr>
<tr><td colspan="2">9. Corporate strategies: 9c Unambitious corporate strategies</td><td colspan="14">9. Corporate strategies: 9a Ambitious corporate strategies</td></tr>
<tr><td colspan="2">10. Relocation of industry: 10a Widespread relocation</td><td colspan="14">10. Relocation of industry: 10c Minor relocation</td></tr>
<tr><td>11. Negative emissions and residual emissions: 11a Low residual emissions and limited use of negative emission technologies</td><td colspan="4">11. Negative emissions and residual emissions: 11b High residual emissions and extensive use of negative emission technologies</td><td colspan="11">11. Negative emissions and residual emissions: 11a Low residual emissions and limited use of negative emission technologies</td></tr>
<tr><td>12. Societal trends: 12c Sufficiency behavior</td><td colspan="5">12. Societal trends: 12a Increasing consumption</td><td colspan="6">12. Societal trends: 12b Constant development</td><td>12. Societal trends: 12a Increasing consumption</td><td colspan="3">12. Societal trends: 12c Sufficiency behavior</td></tr>
</table>

5.4.2. Storylines

5.4.2.1. Slow and delayed change hinders the energy transition ("Delay")

The scenario *Slow and delayed change hinders the energy transition* ("Delay," Table 17, scenario 3 in Table 16) describes a combination of developments on multiple scales which lead to a slow energy transition. Some change occurs, but it is mostly slow and delayed in comparison to decarbonization plans. Globally, a limited availability of PtX products drives prices up. Fossil fuel prices are high too. Unambitious climate policies mean EU ETS reforms are unambitious, leading to comparatively low CO_2 prices, among others. In Germany, policy changes that should accelerate the energy transition are delayed, leading to a continuation of long approval procedures for industrial equipment and renewable energy projects. The expansion of the hydrogen infrastructure experiences a delay as well, as pipelines planned for 2030 are only operational by 2040. By 2045, only industries with no alternative to hydrogen can be supplied with the fuel.

Corporate strategies are unambitious, leading to a slow decarbonization of companies. As a result of the setbacks with PtX (both high prices and low import potentials) and the unambitious corporate strategies and climate policies, key industrial decarbonization technologies are entering the market only late, mostly around 2035, which slows down change. The combination of these factors also leads to a widespread relocation of industry, particularly the production of ammonia and raw iron. The circular economy does not reach its full potential, as material efficiency and recycling rates show only minor improvements. In society, consumption of goods and living area increases, driving up material use and production rates even further. Negative emission technologies are extensively used. Moreover, the expansion of the power grid goes as planned. Yet, these two states remain the exception in an only slowly changing system.

Table 17. The states selected in scenario "Delay."

Descriptor	State
Climate Policies	Unambitious climate policies
Fossil fuel prices	High fossil fuel prices
Power-to-X (PtX) import prices	High import prices
Import potentials of PtX	Low import potentials
Hydrogen infrastructure	Delayed expansion
Power grid expansion	Grid expansion as planned
Market entry of industrial decarbonization technologies	Slow market entry
Circular economy and digitalization	Business-as-usual (BAU)
Corporate strategies	Unambitious corporate strategies
Industrial relocation	Widespread relocation
Negative emissions and residual emissions	High number of negative and residual emissions
Societal trends	Increasing consumption (BAU)

5.4.2.2. *Heavy reliance on PtX ("PtX")*

The scenario *Heavy reliance on PtX* ("PtX," Table 18, scenario 4 in Table 16) describes a world where PtX is widely available, also in industry and the energy sector. This points towards a global boom of renewable energies, meaning that positive developments in Germany are also reflected abroad. Within the EU and Germany, ambitious climate policies are proposed and swiftly adapted. In Germany, industry decarbonizes largely with PtX fuels at low prices, while electrification plays a somewhat less prominent role. As PtX products is widely available, the urgency in the electricity sector is slightly reduced. Associated with this is the delayed expansion of the power grid. In contrast, hydrogen infrastructure develops timely and keeps pace with the fast roll-out of PtX fuels.

Ambitious corporate strategies contribute to reaching decarbonization. The low-cost availability of PtX, combined with ambitious climate policies and corporate strategies, promotes a quick market entry of industrial decarbonization technologies. Policies and ambitious corporate strategies, as well as the low fossil fuel and PtX prices, also help to avoid a large-scale relocation of industry: Only a few, selected industries relocate. At the same time, the availability of PtX, the timely expansion of the hydrogen infrastructure, and the quick market entry of decarbonization technologies promote a BAU development of the circular economy. Developments in the circular economy and digitalization stagnate and at most, moderate improvements are achieved.

Societal trends are constant, meaning that consumption stays on today's level and does not further increase, nor decrease. This trend breaks with developments of recent years toward more individual living space or more individually travelled distance. Lastly, rather than having high residual emissions and strongly depending on negative emission technologies, a reduction in residual emissions takes place.

Table 18. The states selected in scenario "PtX."

Descriptor	State
Climate Policies	Ambitious climate policies
Fossil fuel prices	Low fossil fuel prices
Power-to-X (PtX) import prices	Low import prices
Import potentials of PtX	High import potentials
Hydrogen infrastructure	Timely expansion
Power grid expansion	Delayed grid expansion
Market entry of industrial decarbonization technologies	Quick market entry
Circular economy and digitalization	Business-as-usual (BAU)
Corporate strategies	Ambitious corporate strategies
Industrial relocation	Minor relocation
Negative emissions and residual emissions	Low number of negative and residual emissions
Societal trends	Constant development

5.4.2.3. Rapid scale-up of decarbonization technologies ("Rapid scale-up")

In Scenario *Rapid scale-up of decarbonization technologies* ("Rapid scale-up," Table 19, scenario 12 in Table 16), the main distinct feature is a rapid scale-up of decarbonization technologies. The scenario describes a world where technological development is comparatively balanced. PtX fuels and renewably produced electricity are widely available as well. On the one hand, low PtX import prices, high PtX import potentials, and a timely expansion of hydrogen infrastructure benefit PtX. On the other hand, the grid expansion takes place as planned too and does not impede the electrification of the economy.

Technological advances occur swiftly, allowing for fast implementation of new technologies. These include CCS, PtH applications, and other, industry-specific technologies (MTA, MTO, H2-DRI). Politically and economically, ambitious (supply-side) climate policies and corporate strategies go hand in hand with only a minor relocation of industry. The latter is also benefitted by low PtX prices and the quick market entry of decarbonization technologies.

Despite the slightly promoting influence of high fossil fuel prices and ambitious climate policies and corporate strategies, the circular economy and digitalization are not implemented as widely as possible. Instead, only moderate improvements in material efficiency and recycling are made. High import potentials of PtX, a timely expansion of the hydrogen infrastructure and a quick market entry of decarbonization technologies promote this development. Societal trends are characterized by an increasing consumption, a BAU scenario. People prefer to continue to increase consumption patterns rather than to refrain from doing so. As a result, high residual emissions persist. In order to balance out these emissions, extensive use of negative emission technologies is made.

Table 19. The states selected in scenario "Rapid scale-up."

Descriptor	State
Climate Policies	Ambitious climate policies
Fossil fuel prices	High fossil fuel prices
Power-to-X (PtX) import prices	Low import prices
Import potentials of PtX	High import potentials
Hydrogen infrastructure	Timely expansion
Power grid expansion	Grid expansion as planned
Market entry of industrial decarbonization technologies	Quick market entry
Circular economy and digitalization	Business-as-usual (BAU)
Corporate strategies	Ambitious corporate strategies
Industrial relocation	Minor relocation
Negative emissions and residual emissions	High number of negative and residual emissions
Societal trends	Increasing consumption (BAU)

5.4.2.4. *Societal change*

Scenario "Societal change" (Table 20, scenario 15 in Table 16) describes a world where consumption decreases, and a circular economy unfolds. In this scenario, the demand side also induces change. Sufficiency behavior prevails, leading to reductions in demand and production of industrial goods. In industry, principles of the circular economy are applied: High recycling rates and a strong increase in material efficiency decreases the demand for raw materials even more. Digitalization leads to a more efficient production and a reduction in material demand. At the same time, decarbonization technologies see a rapid market entry, with first applications of key technologies as early as 2025. Very ambitious climate policies, involving both demand and supply measures, promote these trends. They also contribute to the expansion of both the hydrogen and the power grid infrastructure, which develop as planned in the Hydrogen Strategy and the NEP.

Although PtX import prices are low, medium import potentials of PtX fuels allow only a limited application of PtX products in industry and other fields. Hence, direct electrification has a more prominent role than in the scenarios "PtX" and "Rapid scale-up." Cheap fossil fuels are available, but that does not obstruct change: Stimulated by sufficiency trends in society, very ambitious climate policies and the early availability of decarbonization technologies, companies exhibit ambitious climate strategies. The availability of cheap PtX fuels, as well as supporting policies also help to prevent a widespread relocation of the energy-intensive industry. Lastly, the combination of a sufficient society, very ambitious policies and ambitious corporate strategies, as well as a circular economy promotes low residual emissions. Hence, only a limited deployment of negative emission technologies is required.

Table 20. The states selected in scenario "Societal change."

Descriptor	State
Climate Policies	Very ambitious climate policies
Fossil fuel prices	Low fossil fuel prices
Power-to-X (PtX) import prices	Low import prices
Import potentials of PtX	Medium import potentials
Hydrogen infrastructure	Timely expansion
Power grid expansion	Grid expansion as planned
Market entry of industrial decarbonization technologies	Quick market entry
Circular economy and digitalization	Circular economy expanding
Corporate strategies	Ambitious corporate strategies
Industrial relocation	Minor relocation
Negative emissions and residual emissions	Low number of negative and residual emissions
Societal trends	Sufficiency behavior

6. Discussion

6.1. Discussion of results

6.1.1. Logical inconsistency

Although scenarios were selected based on their consistency in ScenarioWizard, the combinations of some of their states appear somewhat illogical. In the "Rapid scale-up" scenario, one would expect circular economy and digitalization to be a dominant state. In scenario "Delay," it seems illogical that grid expansion takes place as planned. Another potentially illogical combination are unambitious climate policies with a widespread relocation of industry, and, vice versa, (very) ambitious climate policies combined with minor relocation. While the shorter approval procedures should make it less likely for industries to relocate, one could also argue that too ambitious climate policies drive companies away, as they attempt to evade rigorous legislation. Even more "logical inconsistencies" could be found when looking at the 16 consistent scenarios, as determined with ScenarioWizard. For example, unambitious climate policies and sufficiency behavior as the dominant societal trend appear in the same scenario. These types of logical inconsistencies are dominant states that emerge from the CIM and the analysis in ScenarioWizard, but that do not necessarily seem to fit to the other states in a chosen scenario. They are further discussed when assessing the methodological approach below. In comparison, other studies, e.g., the "Big Five," do not have to deal with them, as researchers can be more flexible with the creation of their scenario and eliminate such contradictions at an early stage in the planning process. However, they may have other, unidentified inconsistencies in their scenarios, which a CIB approach can reveal [130].

6.1.2. Scenarios and their ability to reach climate neutrality

For all the scenarios presented here, an important caveat holds: They have not been modelled yet. Hence, it is uncertain whether these futures can reach climate neutrality in models. Particularly for scenario "Delay," this is at least doubtful. Key parameters like a late market entry of decarbonization technologies, a low import potential of PtX and unambitious climate policies hint at a challenging path towards decarbonization. At the same time, high CCS capacities could be enough to decarbonize industry, but not other sectors. In comparison, the scenarios "PtX," "Rapid scale-up," and "Societal change" describe worlds where a decarbonization seems very well possible. This is further supported by the observation that these three scenarios appear to be comparable to other scenarios in previous studies, but not scenario "Delay," as discussed in the next chapter. Still, to confirm whether a scenario could achieve climate neutrality according to the current state of science, or not, they would have to be modelled first.

6.1.3. Results in the context of literature

Comparing the scenarios developed here with the "Big Five," it is clear that similar scenarios have been developed before. Several PtX scenarios are present in the literature, whether they are named "More molecules," "Efficient molecules" [11], "Hydrogen" [69, 71], "E-fuels" [69] or "Synthetic hydrocarbons" [71]. Also, a "balanced technology mix" scenario exists and other scenarios that heavily rely on quick implementation of technology [69, 70]. Finally, the Fraunhofer ISE study has thoroughly analyzed the effects of different societal trends on the pathway to climate neutrality [25]. Solely, scenario "Delay" does not have a counterpart in literature, but this is presumably due to the uncertain realization of climate neutrality in that scenario. Where the scenarios presented here differ, is the combination of different developments. In the "Big Five," variation is typically introduced through adaptations of technological assumptions, with other factors held equal [11, 18, 69–71]. Here, they display a wider variety of different states, as combined by the matrix software. The biggest difference, however, lies not so much in the resulting scenarios, but in the scenario planning method, which is discussed in chapter 6.2.4.

6.2. Discussion of method

6.2.1. Descriptor selection

Selecting a set of descriptors that is both concise but also able to convey the key characteristics of a scenario is a major challenge of a CIB analysis. Furthermore, when scenarios are developed for modeling, coupling descriptors are required that connect the scenarios with the model analysis [53]. Another difficulty is the combination of descriptors on global, national, and regional levels [131]. This thesis put a focus on coupling factors that link to the models used in the research project IND-E. Since the research interest of the project is the German industrial decarbonization, this led to a strong representation of descriptors on a national level. This focus on national coupling descriptors led to the non-inclusion of potentially important other factors, e.g., world climate policies.

One approach to avoid the omission of potentially relevant descriptors has been identified by Broll et al. [132]: In their working paper, they first compiled a long list of descriptors. Rather than reducing this list themselves, however, they interviewed experts about which descriptors were exogenous factors that influence other descriptors. This way, they arrived at a final list of eight descriptors, which they had found to be accountable for 80% of exogeneity [132]. Similarly, but less complex, Senkpiel et al. [79] sent a preliminary list of 30 descriptors to experts, who assessed their importance by ranking. This ranking resulted in a list of 15 descriptors, which were then selected for the CIB analysis [79]. Such an approach could make descriptor selection more structured. The disadvantage of these exercises is the increased time consumption. Moreover, a structural problem of CIB analysis remains, which is the limited number of descriptors. The highly aggregated level of analysis leads to exclusion of descriptors that are secondary but nonetheless significant [53]. This limits their ability to "mutually explain their behavior" [53]. In addition, the limited set of descriptors means that not all model parameters can be defined [57]. Modelers must therefore make interpretations in the "'spirit' of the context scenario" [57]. However, this issue is common to all storyline approaches and not limited to CIB analysis. Furthermore, literature also advises against strictly defined quantitative model inputs [53]. In such a case, it is argued, a model would lose its interrogative role and become an illustrative tool instead [133].

Another solution, which partly solves the problem, has been the expansion to more than thirty descriptors, as proposed by Weimer-Jehle ([134], cited in [135]) and applied by Vögele et al. [135]. They solved the issue of overly complicated matrices by using a multi-level approach with sub-matrices. They identified consistent scenarios on a global, a national and a sectoral level and made use of coupling factors between these levels. That way, they could expand their analysis over different levels, include more descriptors and still conduct a CIB analysis [135]. The downside of such an approach is the additional time that is required for performing the analysis.

6.2.2. Filling in the CIM

The completion of the CIM was conducted through a group process, where 2-4 scientists discussed the influences of one descriptor on all other descriptors until they reached consensus. This is a typical CIB process, and group size was comparable to other workshops [136], although larger groups have been employed as well [79, 137]. Such group processes can facilitate inter- and transdisciplinary discourses [53]. They enable exchanges between societal experts and energy modelers, "leading to the identification of important new methodological insights and experiences regarding integrated scenario building" [57]. Yet, the workshops conducted in this thesis also showed some challenges linked to this method. A general issue with group processes is that not everyone's input is necessarily considered for each connection, unlike with individual assessments. Thus, participants that speak up less might contribute less compared to more outspoken group members, regardless of their specific expertise.

Another choice with potentially big impact was the fact that only one group evaluated each descriptor. By doing so, each decision made by a single group had an amplified impact. The difference between filling in a -1 or a +1 in a cross-impact table could very well make certain scenarios possible or prevent others from being judged "consistent." This is particularly problematic when groups make "erroneous judgments," i.e., they do not follow the CIB methodology but also do not record their reasoning in the comments for the evaluator to identify and correct it. It could also be possible that not all relevant influences would be recorded by a group, leading to different assessments. An effort was made to reduce this effect by allowing for small inconsistencies in scenario selection. Still, the "logical inconsistencies" discussed above likely evolve from these kinds of judgments.

Furthermore, groups might have displayed different strategies when filling in the matrix. Some groups might have made disproportional use of extreme values, i.e., -3 or +3, while others refrained from doing so. Although there are clear differences between descriptors (compare, e.g., the two descriptors addressing public infrastructure, "hydrogen infrastructure" and "power grid expansion"), there is no proof of such behavior: Some descriptors will inevitably have a stronger influence than others. However, because only one group filled in each descriptor, different filling-in strategies are certainly possible to have occurred. This is relevant for the interpretation of the CIM and the active-passive diagram.

Moreover, descriptors with more extreme values have a substantially bigger influence on which scenarios become consistent and which not.

Not unique to CIB, but relevant, is that subjectivity of experts plays an important role when filling in the cross-impact table [53]. Storyline construction inevitably builds upon subjective expert assessments, as worldviews shape our perception of things. However, in CIB processes, the formalism of the approach this subjectivity [56]. It would be a misconception to think it would be removed, yet, this limitation is often overlooked in CIB analyses [53]. This potential bias also includes the fact that exclusively scientists did the evaluation, as was noted in chapter 4.3. No other stakeholders, whether activists, entrepreneurs, politicians, or common citizens, participated in the assessment process.

For some of these challenges, methodological adjustments may offer an improvement. Having multiple groups assess descriptors could have several benefits: Firstly, it could balance out "erroneous judgments," leading to more consistent results [53]. Secondly, it could reduce the potential effect of different filling in strategies. Thirdly, it can also reduce subjectivity. For the latter to occur, experts from different fields would have to be invited as well, or other stakeholders. Another option is to ask experts to fill in the cross-impact table individually. That way, it could be easier to obtain multiple judgements of the same descriptor connection. However, it would also remove the advantages of group discussions, which also serve as a filter for outlier opinions and have other benefits, as earlier discussed. Lastly, a process with multiple iterations of filling in the CIM and modeling results could remove inconsistencies [53]. This has repeatedly been recommended in literature (see, e.g., [138]), but is rarely executed: It would significantly lengthen the CIB process [53].

6.2.3. Time consumption of CIB analysis

In fact, time consumption is a major obstacle for many of the recommendations suggested. The additional effort needed would come on top of an already time-consuming process, which a CIB analysis is [53]. Thus, balancing the resources that go into CIB is a key challenge. After all, the level of detail of a CIB analysis is a crucial strength of this approach, but it is expensive to accomplish [139]. It could therefore also be of interest to consider strategies that *shorten* the CIB process, while maintaining a satisfactory level of detail. One way to reduce the expenditure of time could be to decrease the time spent on composing descriptor and state essays. Writing these essays took up a significant amount of the research. At the same time, not all participating experts were able to read the essays before their workshop. Although essays were also consulted during the filling out process, they seemed to rely more on the presentation and discussion to form their opinion on descriptors and states. While this is understandable in the light of work pressure and time constraints, it also takes away from the methodological value of writing these essays in the first place. If experts are not able to read the essays fully, perhaps, this process could be shortened. Alternatively, keywords and values could be used to describe states, or shorter essays could be written. In combination with a detailed presentation, these steps might be enough to provide participants with a common ground for their group discussions when assessing the cross-impact table. Next to providing a baseline for workshop participants, essays have a second function. After the creation of scenarios, one can refer to the essays to see how each state specifically develops. That way, essays contribute to the scenario description of the storyline itself. Hence, if essays were shortened, it might be necessary to add more detail to the storylines.

A different option to shorten the process could be to reduce the number of states per descriptor to two. This suggestion is based on two observations. Firstly, participants generally found the state in between the two extremes difficult to assess, or, typically, judged their impact with a zero. Secondly, these "middle states" were often not included in any consistent scenarios. Three of the six "middle states" did not appear in any of the 16 consistent scenarios, and one appeared only in one scenario. This hints at their redundancy and has also been observed in other research [132]. Only for the descriptors "climate policies" and "societal trends," all three states were utilized somewhat evenly. Hence, reducing states to two and keeping three for only the most influential descriptors could be a viable strategy to further reduce expenditure of time.

6.2.4. Method in the context of literature

Despite the above-mentioned limitations and suggestions for adjusted approaches, the CIB method used in this thesis has aided the process of developing scenarios for a carbon-neutral German industry. While the logical inconsistencies identified are unique to this thesis, other challenges and limitations discussed are also faced in the "Big Five" and other scenario studies. For example, experts filled in the matrix with their subjective worldview, but the approaches chosen in the "Big Five" also leads to subjective assessments of how the future will look. Additionally, although other studies might not display logical inconsistencies, internal inconsistencies are explicitly possible, when analyzed with CIB, as has been shown to be the case for qualitative scenarios in the past [130].

The value of this thesis then also lies in its methodological approach. Where the "Big Five" make implicit assumptions, here, assumptions are presented and discussed. That way, the scenario planning technique is recorded in detail and reproducible. By doing so, this thesis shifts the focus from the results of the process to the assumptions and the process itself. In addition, it opens the door for a discussion about how we imagine the future and how we construct scenarios.

7. Conclusion and Outlook

This thesis sought to answer the following research question: Which consistent scenarios can depict different futures of a carbon-neutral German industry in 2045? It did so through a CIB analysis, an approach that uses expert elicitation to develop consistent scenarios. The method produced 16 consistent scenarios, four of which were selected for a detailed description. Thus, these four scenarios, named “Delay,” “PtX,” “Rapid scale-up,” and “Societal change” were utilized to answer the main research question. The thesis also identified several points of discussion. Descriptor selection could have followed a more structured approach, and issues like potentially erroneous judgments arose from the group assessment in the analysis. Possible remedies, like surveying experts for the descriptor selection or inviting a bigger group of experts, would all lengthen the CIB process. However, CIB is already an exceedingly time-consuming task. Therefore, this thesis also made two suggestions to shorten the process. Firstly, essays describing the different possible developments could be condensed. Keywords and a slideshow could be used to convey the meaning of each development to the participating experts. Secondly, states per descriptor could be reduced to two. Despite these limitations and suggestions, the scenarios developed in this thesis attempted to fulfill the three key roles of scenario development: By investigating and presenting the interactions behind future developments, they aimed to enhance the understanding of the possible future states. By making the typically inherent assumptions explicit, the scenarios are more easily reproducible and can challenge conventional thinking about what drives future developments. Thirdly, the thesis could also be used as a tool to inform decision making.

Next, building upon this thesis, the developed scenarios will be modelled as part of the IND-E project. More insights are to be expected from the modeling stage, both in terms of a more detailed explication of the path towards climate neutrality and for the scenario development process. Finally, the modeling stage will also answer the question of whether timely decarbonization is possible with the assumptions made in the scenarios constructed.

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Appendices

Appendix A: List of model factors relevant for the selection of descriptors (in German)

Sortierte Liste von Szenarienfaktoren /Kombination aus Storyline und möglichen Modellparametern

X = hohe Priorität; Y = kann weg

Storyline	Ausprägung (Qualitativ)	Modellfaktor	Ausprägung	REMod	DISTRICT	PowerFlex	Flexable	TTA	Lastdekompositionstool
Ambition Klimaschutz politisch	KSG | 1,5°C	CO2-Budget/ Ziele		x	x	x			
Internationale Politik (CBA, Klimaclubs)	Auslagerung | keine Auslagerung	Änderung der Nachfrage		x	x	x	x		
Nationale Politik	ambitioniert | BAU	CO2-Preis			x	x	x	x	
Nationale Politik	negative Emissionen forciert | nicht forciert	(BECCS, CO2-Netz, CCS (Prozessemissionen))		?	?				
Ambition Klimaschutz gesellschaftlich	statisch | ambitioniert | planetare Grenzen	Nachfragereduktion Konsumgüter (Produktionsmengen)		(x)			(x)		x
Ambition Klimaschutz gesellschaftlich	statisch | ambitioniert | planetare Grenzen	Änderung der Industriestruktur		x			(x)		x
Ambition Klimaschutz in der Landwirtschaft	konventionell | Bio	Produktionsmengen Stickstoff		(x)			(x)		
Ambition Klimaschutz in der Bauwirtschaft	statisch | ambitioniert	Produktionsmengen Zement		(x)			(x)		
Ambition Klimaschutz in der Bauwirtschaft	statisch | ambitioniert	Produktionsmengen Stahl		(x)			(x)		
Ambition Klimaschutz in Unternehmen	statisch | ambitioniert	Prozesseffizienz		x	x		(x)		
Ambition Klimaschutz in Unternehmen	statisch | ambitioniert	Realisierungszeiten Technologiewechsel / Implementierung		x	x				
Ambition Klimaschutz in Unternehmen	statisch | ambitioniert	Ausschöpfung Potenzial - Elektrifizierung		x	x	x	x	x	x
Ambition Klimaschutz in Unternehmen	statisch | ambitioniert	Ausschöpfung Potenzial - indirekte Elektrifizierung		x	x	x	x	x	
Ambition Klimaschutz in Unternehmen	statisch | ambitioniert	Ausschöpfung Potenzial - Flexibilisierung		(x)	x	x	x	x	x
Ambition Klimaschutz in Unternehmen	statisch | ambitioniert	Produktionsmengen (Produktlebensdauern, Minimierung Verpackungen)		(x)					
Kreislaufwirtschaft	statisch | ambitioniert	Sekundärrouten		(x)					
Kreislaufwirtschaft	statisch | ambitioniert	Reduktion von Primärprodukten		x					
Wirtschaftliche Entwicklungen (makro)		Investitionskosten (Flexibilität, Netze, Wandler)		x				x	
Wirtschaftliche Entwicklungen (makro)		Betriebskosten (Flexibilität, Netze, Wandler)		x	x	x		x	
Wirtschaftliche Entwicklungen (makro)		Brennstoffpreise (Grenzübergang/Bezug)		x		x	x	x	
Wirtschaftliche Entwicklungen (makro)		Importpreise (synthetische Energieträger)		x		x		x	
Wirtschaftliche Entwicklungen (mikro)		Netzentgelte			x				
Wirtschaftliche Entwicklungen (mikro)		PPA			x				
Wirtschaftliche Entwicklungen (mikro)		Strommarkt			x				
Wirtschaftliche Entwicklungen (mikro)		Endverbraucherpreise und Bestandteile (zeitlich/regional)			x			x	
Technologische Innovation	Trend | Beschleunigt	Technologieverfügbarkeit Elektrifizierung		x	x	x		x	
Technologische Innovation	Trend | Beschleunigt	Technologieverfügbarkeit Flexibilisierung		x	x	x		x	
Technologische Innovation	Trend | Beschleunigt	Technologieverfügbarkeit indirekte Elektrifizierung		x	x	x		x	
Infrastruktur	nationaler Ausbau schnell | langsam	inländische Infrastruktur Wasserstoff		(x)	x				
Infrastruktur	globaler Ausbau schnell | langsam	Importmengen Synfuels		x	x				
Infrastruktur	nationaler Ausbau schnell | langsam	Stromnetzausbau			x		x		
Infrastruktur	nationaler Ausbau schnell | langsam	Wasserstoffelektrolyseure			x	x	x		
Verkehr	statisch | ambitioniert	Personenkilometer							
Gebäude	statisch | ambitioniert	Pro-Kopf Fläche							
Produkt Import-Exportbilanz									

Appendix B: List of preliminary descriptors

Politics (national)	International	Economy	Society	Technology and Innovation	Infrastructure
Political ambitions climate protection	International ambitions climate protection	GDP/capita	Societal ambitions climate protection	Battery prices and capacities	Hydrogen infrastructure
Political stability energy	Expansion and integration of European infrastructure (hydrogen, power)	Industrial relocation	Living trends (m^2/person)	Hydrogen prices and capacities	Grid expansion
	CO_2 price	Willingness to invest	Consumption behavior	Industrial electrification	Building refurbishment
	Fossil fuel price (oil, gas)	Development agriculture	Mobility patterns	Circular economy	Expansion public transport
	Synthetic fuel import price	Development construction sector		Efficiency development	Expansion renewable energies
	Hydrogen import price	Economic micro development		Carbon capture and storage	

Klimapolitischer Rahmen

Mix aus EU und nationaler Klimapolitik, die den Übergang zu einer klimaneutralen Gesellschaft lenken

Ausprägungen:

Progressive Klimapolitik

- Breite Anwendung von Carbon Contracts for Difference (CCfDs) und anderen Mitteln zur Finanzierung
- EU ETS Reformen wie vorgeschlagen im Rahmen des Green Deals (u.a. schnellere Reduktion der freien Emissionszuteilung) werden implementiert
- CO_2 Preis 2030: 140 €/t-CO_2, 2045: 500 €/t-CO_2
- Dauer von Genehmigungsverfahren wird auf 2-3 Jahre verkürzt
- Netzentgelte werden zeitnah reformiert

Unambitionierte Klimapolitik

- EU ETS Reformen werden verzögert implementiert, CO_2 Preis bleibt konstant bis 2030
- CO_2 Preis 2030: 85 €/t-CO_2, 2045: 250 €/t-CO_2
- Dauer von Genehmigungsverfahren bleibt bei ungefähr 5 Jahren in Industrie
- Netzentgeltreform erst nach 2027

5

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Wirtschaftliche Entwicklung

Wird gemessen in Bruttoinlandsprodukt (BIP)

Ausprägungen:

Wachstum

- Durchschnittliches Wachstum von 1% pro Jahr zw. 2025 und 2045

Stagnation

- 0% Wachstum zw. 2025 und 2045

Rezession

- -0,5% Wachstum pro Jahr zw. 2025 und 2045

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Fossile Treibstoffpreise

Beschreibt die Preisentwicklung bei Gas, Öl und Steinkohle

Ausprägungen:

Hohe Preise

- Anhaltende Spannungen zwischen Europa und Russland
- Starke Diversifikation bei Importen, u.a. auch viel Import von LNG

Niedrige Preise

- Geopolitische Entspannung tritt ein – Importe aus Russland nehmen wieder zu
- Moderate Diversifikation von Energieimporten

Year	'25	'26	'27	'28	'29	'30	'31	'32	'33	'34	'35	'36	'37	'38	'39	'40	'41	'42	'43	'44	'45
Low fossil fuel import prices																					
Gas (€/MWh)	46	42	38	34	29	25	25	25	25	25	26	26	26	26	26	26	26	26	26	26	27
Oil (€/MWh [€/bbl])	40 [66]	42 [68]	43 [70]	44 [72]	45 [74]	46 [75]	47 [76]	47 [76]	47 [77]	48 [78]	48 [78]	48 [79]	49 [79]	49 [80]	49 [80]	50 [81]	50 [81]	50 [82]	51 [82]	51 [83]	51 [83]
Coal (€/MWh [€/t])	13 [105]	12 [97]	11 [89]	10 [81]	9 [73]	8 [66]	8 [65]	8 [65]	8 [65]	8 [65]	8 [65]	8 [64]	8 [64]	8 [64]	8 [64]	8 [64]	8 [63]	8 [63]	8 [63]	8 [63]	8 [63]
High fossil fuel import prices																					
Gas (€/MWh)	77	72	66	61	56	50	50	51	51	51	51	51	52	52	52	52	52	53	53	53	53
Oil (€/MWh [€/bbl])	63 [102]	64 [104]	65 [106]	67 [109]	68 [111]	69 [113]	70 [114]	70 [115]	71 [116]	71 [116]	72 [117]	72 [118]	73 [119]	73 [120]	74 [120]	74 [121]	75 [122]	75 [123]	76 [124]	76 [124]	77 [125]
Coal (€/MWh [€/t])	17 [139]	15 [125]	14 [112]	12 [99]	10 [85]	9 [72]	9 [72]	9 [72]	9 [72]	9 [71]	9 [71]	9 [71]	9 [71]	9 [70]	9 [70]	9 [70]	9 [70]	9 [70]	9 [69]	8 [69]	8 [69]

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Power-to-X (PtX) Importpreise

Beschreibt die Preisentwicklung bei H_2, synthetischem Methan und E-Fuels

Ausprägungen:

Hohe Preise

- Weniger schnelle techn. Entwicklung und geringere Produktion, bei gleichzeitig hohem Bedarf führen zu hohen Preisen

Niedrige Preise

- Schnelle Entwicklung, hohe Produktion, u.a. in geografisch nahen Ländern führen zu niedrigeren Preisen

Scenario (Year)	Import costs (€/MWh)		
	Hydrogen	Synthetic methane	Liquid fuels
High (2030)	174	205	190
High (2045)	134	155	143
Low (2030)	137	158	143
Low (2045)	103	116	99

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Importpotenziale PtX

Beschreibt die möglichen Importmengen von H_2, synthetischem Methan und E-Fuels

Ausprägungen:

Hohes Importpotenzial

- Sehr schnelle Entwicklung des Weltmarktes, viele Importpartner DE
- Importinfrastruktur schnell entwickelt und in Abstimmung mit EU

Mittleres Importpotenzial

- Gute Entwicklung des Weltmarktes, einige Importpartner DE
- Importinfrastruktur in normaler Geschwindigkeit entwickelt und in Abstimmung mit EU

Niedriges Importpotenzial

- Langsame Entwicklung des Weltmarktes, wenige Importpartner DE
- Importinfrastruktur langsam entwickelt und nicht immer in Abstimmung mit EU, fragmentierter EU Markt

Scenario	Import potential (TWh/yr in 2045)		
	Hydrogen	Synthetic methane	Liquid fuels
High	250	200	200
Medium	200	135	135
Low	100	30	30

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Wasserstoffinfrastruktur

Innerdeutsche H_2-Infrastruktur, die auch an internationale H_2-Netze anschließt

Ausprägungen:

Zeitiger Ausbau: Nach Nationaler Wasserstoffstrategie

- 2030: Produktionskapazität 5 GW → 14 TWh H_2
- 2045: Produktionskapazität 36 GW → 100 TWh H_2
- → H_2 prinzipiell in Industrie verfügbar

Verzögerter Ausbau

- 2030: Produktionskapazität 3.6 GW → 10 TWh H_2
- 2045: Produktionskapazität 18 GW → 50 TWh H_2
- → H_2 nur verfügbar, wo alternativlos

Stromnetzausbau

Ausbau des deutschen Stromnetzes, um Verdopplung des Elektrizitätskonsums bis 2045 zu stemmen und Ausbau von Erneuerbaren zu ermöglichen

Ausprägungen:

Ausbau nach Netzentwicklungsplan

- Suedlink fertig bis 2028, SuedOstLink bis 2027
- Ausbau hält Schritt mit zunehmender Nachfrage

Verzögerter Stromnetzausbau

- Verspätungen bei Projekten
- Großprojekte meist 5 Jahre verspätet – Suedlink und SuedOstLink werden erst 2033 und 2032 fertiggestellt
- Weniger Verfügbarkeit von erneuerbar produzierter Elektrizität für industrielle und private Nachfrage

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Technoökonomische Entwicklung von Industriedekarbonisierungs-technologien

Beschreibt die Geschwindigkeit der Implementierung neuer Technologien, anhand der ersten Markteinführung (und anschließendem Roll-out und Upscaling)

Ausprägungen: Schnell, Mittel, Langsam

Sector	Technology	TRL in 2019 [55]	Market entry		
			Slow	Medium	Fast
Iron and steel	Hydrogen direct reduction ironmaking	4-5	2035	2030	2025
Chemical industry	Methanol-to-olefins	8	2035	2030	2025
Chemical industry	Methanol-to-aromatics	6	2035	2030	2025
Cement industry	CO_2 capturing through oxyfuels	6	2035	2030	2025
Cross-sector	Power-to-heat: Electrode boiler (up to 500°C)	8-9	2025	2023	2023
Cross-sector	Power-to-heat: High temperature heat pump (above 150°C)	5-7 [58]	2030	2025	2023

Kreislaufwirtschaft und Digitalisierung

Beschreibt den Ausbau der Kreislaufwirtschaft und der Digitalisierung, um durch Recycling, Produktdesign, Materialsubstitution, Abfallvermeidung, verlängerter Lebensdauer und Informationsaustausch den Ressourcenverbrauch zu reduzieren

Ausprägungen:

Kreislaufwirtschaft

- Große Verbesserungen bei Materialeffizienz und Recyclingraten

Product	Recycling rates in 2045
Steel	60% recycled steel used (today: 30%)
Plastics	15 percentage points increase in recycling (mechanical and chemical)
Paper	85% recycling rate (today: 77%)
Aluminum	80% recycled aluminum used (today: 54%)

Business-as-usual

- Leichte Verbesserungen bei Materialeffizienz und Recycling

Product	Recycling rates in 2045
Steel	35% recycled steel used (today: 30%) [37]
Paper	80% recycling of old paper (today: 77%)
Aluminum	62% recycled aluminum used (today: 54%) [37]

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Kreislaufwirtschaft und Digitalisierung

Kreislaufwirtschaft

Product	Decrease in production (2045) compared to reference	Explanation
Crude steel	10%	More efficient use of steel and material substitution
Aluminum	<5%	Decrease in demand
Paper	10%	Trend to paperless applications (digitalization)
Container glass	15%	Efficient use of materials
Cement	15%	Material efficiency in the construction sector
Cement clinker	37%	Substitution with other materials
Lime	30%[1]	Strong decrease through phase-out of coal-fired power generation and through switch from blast furnace to other steel production
Ammonia	20%	More efficient fertilizing techniques
Plastics	15%	Decrease in use, e.g., packaging material

[1] Value adjusted after consultation with author.

Business-as-usual

Product	Decrease in production (2045) compared to reference	Explanation
Crude steel	0%	Constant steel demand [37]
Aluminum	0%	No change
Paper	0%	No change
Container glass	5%	Slightly more efficient use of materials
Cement	5%	Slightly improved material efficiency in the construction business
Cement clinker	27%	Substitution through other materials
Lime	10%	Decrease through phase-out of coal-fired power generation and through switch from blast furnace to other steel production
Ammonia	10%	Somewhat efficient fertilizing techniques
Plastics	5%	Slight decrease in use, e.g., packaging material

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Unternehmensstrategien

Unternehmensstrategien zum Erreichen der Klimaneutralität: Ziele der Unternehmen, Abhängigkeit von CO_2-Ausgleich, Implementierung neuer Technologien

Ausprägungen:

Ambitionierte Unternehmen

- 50% der Unternehmen bis 2030 klimaneutral, 100% bis 2045
- Generell: So wenig (negative) ausgleichende Emissionen wie möglich, klare Zeitpläne, schnelle Implementierung neuer Technologien

Mittelmäßig ambitionierte Unternehmen

- Bis 2030 20% der Unternehmen klimaneutral, 50% bis 2045
- Manche Unternehmen ziehen mit, andere weniger. Neue Technologien werden genutzt, aber nicht immer sofort

Unambitionierte Unternehmen

- Bis 2030 wollen 5% der Unternehmen klimaneutral sein, 20% bis 2045
- Neue Technologien werden verlangsamt genutzt, verschiedene Definitionen und Standards verwendet

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Industrieverlagerung

Beschreibt die Abwanderung der deutschen (energieintensiven) Industrie anhand von Ammoniak- sowie Eisen- und Stahlindustrie

Ausprägungen:

Hohe Abwanderungsraten

- Bis 2030: Drittel der Eisen- und Stahlindustrie wandert ab, gesamte Ammoniakproduktion wird ins Ausland verlagert
- Bis 2045: 50% der heutigen Produktion von Eisen und Stahl im Ausland

Mittlere Abwanderungsraten

- Bis 2030: Sechstel der Eisen- und Stahlindustrie wandert ab, 50% der Ammoniakproduktion wird ins Ausland verlagert
- Bis 2045: Kaum weitere Abwanderung Eisen- und Stahl, 75% der heutigen Ammoniakproduktion im Ausland

Kaum Abwanderung

- Bis 2030: 30% der Ammoniakproduktion im Ausland
- Bis 2045: Keine weitere Abwanderung Ammoniak, Eisen und Stahl bleibt auf heutigem Level

Negative Emissionen

Beschreibt die Verwendung negativer Emissionstechnologien, um Residualemissionen auszugleichen

Ausprägungen:

Limitierte Nutzung negativer Emissionen

- Langsamere und skeptischere Annahme von negativen Emissions- und CO_2-Speichertechnologien
- Reduktion von Residualemissionen auf Minimum
- Starke Reduktion des Tierbestands, effizientere Nutzung von Dünger
- 11 Mt-CO_2-eq von LULUCF
- 38 Mt-CO_2-eq von BECC und DACC

Hohe Nutzung negativer Emissionen

- Technologieaffinität, schnelle Annahme von negativen Emissions- und CO_2-Speichertechnologien
- Geringere Reduktion der Residualemissionen
- Geringere Reduktion Tierbestand, weniger CCS von Prozessemissionen
- 11 Mt-CO_2-eq von LULUCF
- 57 Mt-CO_2-eq von BECC und DACC

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Gesellschaftliche Entwicklung

Beschreibt mögliche Entwicklung in der Gesellschaft, v.a. anhand von Konsum, Wohnfläche und Mobilität

Ausprägungen:

Steigender Konsum

- Gegenentwicklung zur Klimabewegung (Bsp. SUVs)
- Generell höherer Verbrauch: Wohnfläche und Verbrauchsgüter, erhöhter Individualverkehr

Durchschnittliche Entwicklung

- „Normale" Entwicklung von Wohnfläche, Individualverkehr und Verbrauchsgütern

Suffizienzverhalten

- Nachhaltigere Lebensweisen ziehen mehr Leute an, Verbrauch wird freiwillig eingeschränkt
- Reduktion von Verbrauch bei Wohnfläche, Individualverkehr und Verbrauchsgütern

	Average living area per person (m^2)		Production output as a result of demand for consumer goods	Motorized private transport (billion passenger-kilometers)	
	2030	2045	2045	2030	2045
Increasing Consumption	52.7	61.1	120%	1,056	1,083
Balanced development	49.1	51.5	100%	851	872
Sufficiency behavior	41.6	47.7	80%	788	526

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Appendix D: Presentation after discussion

Klimapolitischer Rahmen

Mix aus EU und nationaler Klimapolitik, die den Übergang zu einer klimaneutralen Gesellschaft lenken

Ausprägungen:

Sehr ambitionierte Klimapolitik

- Ambitionierte Angebots- und Nachfrage´-orientierte Klimapolitik
- Breite Anwendung von Carbon Contracts for Difference (CCfDs) und anderen Mitteln zur Finanzierung
- EU ETS Reformen wie im Rahmen des Green Deals werden implementiert
- Dauer von Genehmigungsverfahren wird auf 2-3 Jahre verkürzt (Industrie und EE-Ausbau)
- Netzentgelte werden zeitnah reformiert

Ambitionierte Klimapolitik

Ambitionierte Angebots-orientierte Klimapolitik

- Breite Anwendung von Carbon Contracts for Difference (CCfDs) und anderen Mitteln zur Finanzierung
- EU ETS Reformen wie im Rahmen des Green Deals werden implementiert
- Dauer von Genehmigungsverfahren wird auf 2-3 Jahre verkürzt (Industrie und EE-Ausbau)
- Netzentgelte werden zeitnah reformiert

BAU-Klimapolitik

- BAU Angebots-orientierte
- EU ETS Reformen werden verzögert implementiert
- Dauer von Genehmigungsverfahren bleibt bei ungefähr 5 Jahren in Industrie und EE
- Netzentgeltreform erst nach 2027

5

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Fossile Brennstoffpreise

Beschreibt die Preisentwicklung bei Gas, Öl und Steinkohle

Ausprägungen:

Hohe Preise

- Starke Diversifikation bei Importen, u.a. auch viel Import von LNG

Niedrige Preise

- Geopolitische Entspannung tritt ein
- Moderate Diversifikation von Energieimporten

Year	'25	'26	'27	'28	'29	'30	'31	'32	'33	'34	'35	'36	'37	'38	'39	'40	'41	'42	'43	'44	'45
Low fossil fuel import prices																					
Gas (€/MWh)	46	42	38	34	29	25	25	25	25	25	26	26	26	26	26	26	26	26	26	26	27
Oil (€/MWh [€/bbl])	40 [66]	42 [68]	43 [70]	44 [72]	45 [74]	46 [75]	47 [76]	47 [76]	47 [77]	48 [78]	48 [78]	48 [79]	49 [79]	49 [80]	49 [80]	50 [81]	50 [81]	50 [82]	51 [82]	51 [83]	51 [83]
Coal (€/MWh [€/t])	13 [105]	12 [97]	11 [89]	10 [81]	9 [73]	8 [66]	8 [65]	8 [65]	8 [65]	8 [65]	8 [65]	8 [64]	8 [64]	8 [64]	8 [64]	8 [64]	8 [63]	8 [63]	8 [63]	8 [63]	8 [63]
High fossil fuel import prices																					
Gas (€/MWh)	77	72	66	61	56	50	50	51	51	51	51	51	52	52	52	52	52	53	53	53	53
Oil (€/MWh [€/bbl])	63 [102]	64 [104]	65 [106]	67 [109]	68 [111]	69 [113]	70 [114]	70 [115]	71 [116]	71 [116]	72 [117]	72 [118]	73 [119]	73 [120]	74 [120]	74 [121]	75 [122]	75 [123]	76 [124]	76 [124]	77 [125]
Coal (€/MWh [€/t])	17 [139]	15 [125]	14 [112]	12 [99]	10 [85]	9 [72]	9 [72]	9 [72]	9 [72]	9 [71]	9 [71]	9 [71]	9 [71]	9 [70]	9 [70]	9 [70]	9 [70]	9 [70]	9 [69]	8 [69]	8 [69]

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Power-to-X (PtX) Importpreise

Beschreibt die Preisentwicklung bei H_2, synthetischem Methan und E-Fuels

Ausprägungen:

Hohe Preise

- Weniger schnelle techn. Entwicklung und geringere Produktion, bei gleichzeitig hohem Bedarf führen zu hohen Preisen

Niedrige Preise

- Schnelle Entwicklung, hohe Produktion zu niedrigeren Preisen

Scenario (Year)	Import prices (€/MWh)		
	Hydrogen	Synthetic methane	Liquid fuels
High (2030)	174	205	190
High (2045)	134	155	143
Low (2030)	137	158	143
Low (2045)	103	116	99

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Importpotenziale PtX

Beschreibt die möglichen Importmengen von H_2, synthetischem Methan und E-Fuels

Ausprägungen:

Hohes Importpotenzial

- Sehr schnelle Entwicklung des Weltmarktes, viele Importpartner DE
- Importinfrastruktur schnell entwickelt und in Abstimmung mit EU

Mittleres Importpotenzial

- Gute Entwicklung des Weltmarktes, einige Importpartner DE
- Importinfrastruktur in normaler Geschwindigkeit entwickelt und in Abstimmung mit EU

Niedriges Importpotenzial

- Langsame Entwicklung des Weltmarktes, wenige Importpartner DE
- Importinfrastruktur langsam entwickelt und nicht immer in Abstimmung mit EU, fragmentierter EU Markt

Scenario	Import potential (TWh/yr in 2045)		
	Hydrogen	Synthetic methane	Liquid fuels
High	250	200	200
Medium	200	135	135
Low	100	30	30

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Wasserstoffinfrastruktur

Innerdeutsche H_2-Infrastruktur, die auch an internationale H_2-Netze anschließt

Ausprägungen:

Zeitiger Ausbau: Nach Nationaler Wasserstoffstrategie

- 2030: Produktionskapazität 5 GW → 14 TWh H_2
- 2045: Produktionskapazität 36 GW → 100 TWh H_2
- → H_2 prinzipiell in Industrie verfügbar

Verzögerter Ausbau

- 2030: Produktionskapazität 3.6 GW → 10 TWh H_2
- 2045: Produktionskapazität 18 GW → 50 TWh H_2
- → H_2 nur verfügbar, wo alternativlos

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Stromnetzausbau

Ausbau des deutschen Stromnetzes, um Verdopplung des Elektrizitätskonsums bis 2045 zu stemmen und Ausbau von Erneuerbaren zu ermöglichen

Ausprägungen:

Ausbau nach Netzentwicklungsplan

- Suedlink fertig bis 2028, SuedOstLink bis 2027
- Ausbau hält Schritt mit zunehmender Nachfrage

Verzögerter Stromnetzausbau

- Verspätungen bei Projekten
- Großprojekte meist 5 Jahre verspätet – Suedlink und SuedOstLink werden erst 2033 und 2032 fertiggestellt
- Weniger Verfügbarkeit von erneuerbar produzierter Elektrizität für industrielle und private Nachfrage

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Markteintritt von Industriedekarbonisierungstechnologien

Beschreibt die Geschwindigkeit der Implementierung neuer Technologien, anhand der ersten Markteinführung (und anschließendem Roll-out und Upscaling)

Ausprägungen: Schnell, Mittel, Langsam

Sector	Technology	TRL in 2019 [55]	Market entry		
			Slow	Medium	Fast
Iron and steel	Hydrogen direct reduction ironmaking	4-5	2035	2030	2025
Chemical industry	Methanol-to-olefins	8	2035	2030	2025
Chemical industry	Methanol-to-aromatics	6	2035	2030	2025
Cement industry	CO_2 capturing through oxyfuels	6	2035	2030	2025
Cross-sector	Power-to-heat: Electrode boiler (up to 500°C)	8-9	2025	2023	2023
Cross-sector	Power-to-heat: High temperature heat pump (above 150°C)	5-7 [58]	2030	2025	2023

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Kreislaufwirtschaft und Digitalisierung

Beschreibt den Ausbau der Kreislaufwirtschaft und der Digitalisierung, um durch Recycling, Produktdesign, Materialsubstitution, Abfallvermeidung, verlängerter Lebensdauer und Informationsaustausch den Ressourcenverbrauch zu reduzieren

Ausprägungen:

Kreislaufwirtschaft

- Große Verbesserungen bei Materialeffizienz und Recyclingraten

Product	Recycling rates in 2045
Steel	60% recycled steel used (today: 30%)
Plastics	15 percentage points increase in recycling (mechanical and chemical)
Paper	85% recycling rate (today: 77%)
Aluminum	80% recycled aluminum used (today: 54%)

Business-as-usual

- Leichte Verbesserungen bei Materialeffizienz und Recycling

Product	Recycling rates in 2045
Steel	35% recycled steel used (today: 30%) [37]
Paper	80% recycling of old paper (today: 77%)
Aluminum	62% recycled aluminum used (today: 54%) [37]

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Kreislaufwirtschaft und Digitalisierung

Kreislaufwirtschaft

Product	Decrease in production (2045) compared to reference	Explanation
Crude steel	10%	More efficient use of steel and material substitution
Aluminum	<5%	Decrease in demand
Paper	10%	Trend to paperless applications (digitalization)
Container glass	15%	Efficient use of materials
Cement	15%	Material efficiency in the construction sector
Cement clinker	37%	Substitution with other materials
Lime	30%[1]	Strong decrease through phase-out of coal-fired power generation and through switch from blast furnace to other steel production
Ammonia	20%	More efficient fertilizing techniques
Plastics	15%	Decrease in use, e.g., packaging material

[1] Value adjusted after consultation with author.

Business-as-usual

Product	Decrease in production (2045) compared to reference	Explanation
Crude steel	0%	Constant steel demand [37]
Aluminum	0%	No change
Paper	0%	No change
Container glass	5%	Slightly more efficient use of materials
Cement	5%	Slightly improved material efficiency in the construction business
Cement clinker	27%	Substitution through other materials
Lime	10%	Decrease through phase-out of coal-fired power generation and through switch from blast furnace to other steel production
Ammonia	10%	Somewhat efficient fertilizing techniques
Plastics	5%	Slight decrease in use, e.g., packaging material

Unternehmensstrategien

Unternehmensstrategien zum Erreichen der Klimaneutralität: Ziele der Unternehmen, Abhängigkeit von CO_2-Ausgleich, Implementierung neuer Technologien

Ausprägungen:

Ambitionierte Unternehmen

- Generell: klare Zeitpläne, schnelle Implementierung neuer Technologien
- Innovationskraft durch Vorreiterrolle einzelner Unternehmen tendenziell stärker ausgeprägt

Mittelmäßig ambitionierte Unternehmen

- Manche Unternehmen ziehen mit, andere weniger. Neue Technologien werden genutzt, aber nicht immer sofort
- Innovationskraft durch Vorreiterrolle einzelner Unternehmen weniger stark ausgeprägt

Unambitionierte Unternehmen

- Neue Technologien werden verlangsamt genutzt, verschiedene Definitionen und Standards verwendet
- Kaum Verbreitete Innovationskraft durch Vorreiterrolle einzelner Unternehmen weniger stark ausgeprägt

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Industrieverlagerung

Beschreibt die Abwanderung der deutschen (energieintensiven) Industrie anhand von Ammoniak- sowie Eisen- und Stahlindustrie

Ausprägungen:

Hohe Abwanderungsraten

- Bis 2030: Drittel der Eisen- und Stahlindustrie wandert ab, gesamte Ammoniakproduktion wird ins Ausland verlagert
- Bis 2045: 50% der heutigen Produktion von Eisen und Stahl (insb. Eisenschwamm) im Ausland

Mittlere Abwanderungsraten

- Bis 2030: Sechstel der Eisen- und Stahlindustrie wandert ab, 50% der Ammoniakproduktion wird ins Ausland verlagert
- Bis 2045: Kaum weitere Abwanderung Eisen- und Stahl, 75% der heutigen Ammoniakproduktion im Ausland

Kaum Abwanderung

- Bis 2030: 30% der Ammoniakproduktion im Ausland
- Bis 2045: Keine weitere Abwanderung Ammoniak, Eisen und Stahl (insb. Eisenschwamm) bleibt auf heutigem Level

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Negative Emissionen und Residualemissionen

Beschreibt die Verwendung negativer Emissionstechnologien, um Residualemissionen auszugleichen

Ausprägungen:

Limitierte Nutzung negativer Emissionen

- Langsamere und skeptischere Annahme von negativen Emissions- und CO_2-Speichertechnologien
- Starke Reduktion der Residualemissionen
- Starke Reduktion des Tierbestands, effizientere Nutzung von Dünger
- 38 Mt-CO_2-eq von BECCS und DACCS im Jahr 2045

Hohe Nutzung negativer Emissionen

- Technologieaffinität, schnelle Annahme von negativen Emissions- und CO_2-Speichertechnologien
- Geringere Reduktion der Residualemissionen
- Geringere Reduktion Tierbestand, ~~weniger CCS von Prozessemissionen~~
- 57 Mt-CO_2-eq von BECCS und DACCS im Jahr 2045

Gesellschaftliche Entwicklung

Beschreibt mögliche Entwicklung in der Gesellschaft, v.a. anhand von Konsum, Wohnfläche und Mobilität

Ausprägungen:

Business as usual

- Generell höherer Verbrauch: Wohnfläche und Verbrauchsgüter, erhöhter Individualverkehr

Konstante Fortschreibung

- Werte von Entwicklung von Wohnfläche, Individualverkehr und Verbrauchsgütern bliebt konstant

Suffizienzverhalten

- Nachhaltigere Lebensweisen ziehen mehr Leute an, Verbrauch wird freiwillig eingeschränkt
- Reduktion von Verbrauch bei Wohnfläche, Individualverkehr und Verbrauchsgütern

	Average living area per person (m²)		Production output as a result of demand for consumer goods	Motorized private transport (billion passenger-kilometers)	
	2030	2045	2045	2030	2045
Increasing Consumption (BAU)	52.7	61.1	120%	1,056	1,083
Balanced development	49.1	51.5	100%	851	872
Sufficiency behavior	~~47.7~~	~~41.6~~	80%	~~788~~	~~526~~

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Appendix E: Google Sheet link

https://docs.google.com/spreadsheets/d/1AAjcsMCDFGoxVDE5kAd1e-qDyb_FNU8V4mFuh2oRirs/edit?usp=sharing

Appendix F: Distribution of states selected in the 16 consistent scenarios