Building ambitious low-carbon scenarios

A participatory approach applied to Germany

Project: ENCI-LowCarb

Engaging Civil Society in Low-carbon Scenarios

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Building ambitious low carbon scenarios - A participatory approach applied to Germany, ENCI-LowCarb project report

Eva Schmid, Brigitte Knopf and Jan Burck

Abstract

This reports presents one important outcome from the German working package of the EU FP7 project *Engaging Civil Society in Low-Carbon Scenarios*. It presents a set of long-term, model-based mitigation scenarios for Germany that integrate the technological, economic and socio-political dimensions of ambitious domestic CO_2 abatement. Civil society stakeholders from the transport and electricity sector framed the definition of boundary conditions for the energy-economy model REMIND-D and evaluated the scenarios by means of a participatory approach. All scenarios achieve 85% CO_2 emission reduction in 2050 relative to 1990.

Model results indicate that a continuation of historical trends in the freight transport and electricity sector deemed likely by stakeholders, leads to a carbon lock-in accounting for 55% of the total CO2 budget until 2050. Enforcing ambitious mitigation despite the carbon lock-in slows down economic growth and entails severe socio-political externalities. These render ambitious domestic mitigation extremely challenging. Mitigation costs can be halved if the carbon lock-in is resolved and energy efficiency growth rates increase along with renewable electricity generation. Technologies that face social acceptance problems, such as CCS, can decrease mitigation costs even further, but not substantially. In order to avoid a carbon lock-in major paradigm shifts need to occur, which in return require concerted political action as much as societal will.

Content

List of Abbreviations

CCS = Carbon Capture and Sequestration
CSO = Civil Society Organization
ENCI LowCarb = Engaging Civil Society in Low Carbon Scenario
EU = European Union
GDP = Gross Domestic Product
GW = Gigawat
Gt = Gigaton
HHS = Households
IAM = Integrated Assessment Model
IND = Industry
MIT = Motorized Individual Transport
MS = Modal Split
NGO = Non-Governmental Organization
PP = Power Plant
PT = Public Transport
REG = Renewable Electricity Generation
STD = Standard Deviation
TL = Transmission Line

1. Introduction

Ambitious domestic mitigation efforts by industrialized countries are necessary for maintaining a likely chance to keep global warming below 2°C (UNEP, 2010). The European Union has committed itself to reduce CO_2 emissions by 20% in 2020, relative to those in 1990 (European Parliament and the European Council, 2009). Member states share the mitigation effort according to individual capabilities. This decision led Germany to target a 21% cut in domestic CO_2 emissions in the short-term and to a 40% emissions reduction target by 2020. In the long-term, the German Government endorses an ambitious target of 80-95% CO_2 emission reduction by 2050, relative to 1990 (Bundesregierung, 2010).

Several comprehensive scenario studies based on energy-system models have demonstrated that achieving this long-term goal is technically feasible (e.g. Schlesinger et al., 2010; Nitsch and Wenzl, 2009; Nitsch et al., 2010; Kirchner et al., 2009). Model results indicate that best available technologies will have to penetrate the market in large scale. To achieve this, rigorous energy policy measures with far-reaching implications for the German society are required. Yet it was not subject of analysis in the scenario studies whether their projected developments and derived energy policy suggestions align with public preferences. In case they do not align, public refusal to adopt or allow for the adoption of best available technologies may challenge ambitious mitigation. A prominent example of public refusal is local opposition formation against onshore wind farms, due to e.g. negative landscape externalities (Meyerhoff et al., 2010). Since local oppositions and other acts of public refusal can severely delay the rapid and large-scale deployment of best available technologies, the notion of 'social acceptance' has become a keyword in the energy policy arena. The Ethics Commission for a Safe Energy Supply, appointed by the Federal Government, argues that in order to ensure a high level of public acceptance for the energy supply, transparency in the decisions made by both parliament and government as well as participation by social groups in the decision making process is a prerequisite (2011).

As mitigation scenarios examine what is technologically feasible and inform the energy policy process, transparency and participation must also increasingly become part of their design and development. To date, quantitative modelbased scenarios are generally developed by experts and their analysis is largely dominated by techno-economic considerations. In order to generate scenarios that also consider public preferences, participative approaches to scenario development are intriguing.

A careful deliberation of mitigation options requires that direct and indirect implications of mitigation options are considered, discussed and reflected by the spectrum of affected stakeholders, collectively. The development and analysis of model-based mitigation scenarios that explicitly take into account stakeholders' judgments and preferences can enhance the understanding of societal challenges towards ambitious mitigation. For deriving such scenarios, stakeholders' judgments and preferences need to be elicited and translated to configurations of model input parameters. Model results then carry contextual, normative meaning and enable substantive discussions on the socio-political externalities of technology-focused mitigation pathways. This can only be achieved in a participatory approach in which deliberation frames analysis, and analysis informs deliberation.

Examples of participatory approaches to model-based mitigation scenarios are scarce in the literature. The scenarios of the 'Roadmap 2050 for a low carbon economy' by the European

Commission (2011) have been assessed on their impact through an online questionnaire, which is a unilateral method only. The European Climate Foundation (ECF) periodically consulted a wide range of stakeholders throughout the preparation of mitigation scenarios for their 'Roadmap 2050' (ECF, 2010), but the concrete procedure is not described. To the authors' knowledge, there are so far no contemporary applications of participatory approaches to developing ambitious mitigation scenarios for Germany. The aim of the project was to fill the gap by presenting a set of model-based, long-term mitigation scenarios for Germany that are denied and evaluated in a participatory process with civil society organization (CSO) stakeholders from the transport and electricity sector. It addresses the domestic mitigation challenges not only from a techno-economic point of view, but also from a socio-political perspective by combining both analytical and deliberative elements in a participatory methodology. The exploratory research was conducted as a part of the EU project ENCI LowCarb (Engaging Civil Society in Low Carbon Scenarios). In dedicated stakeholder dialogues, CSO representatives discussed available mitigation options for the transport and electricity sector. Their judgments and preferences framed the scenario definition and corresponding parameter configurations for the hybrid energy-economy model REMIND-D (Schmid et al., 2012). REMIND-D is based on the structural equations of the state-of-the art global Integrated Assessment Model (IAM) REMIND-R (Leimbach et al., 2010). Since REMIND-D is a hybrid model, integrating a detailed bottom-up energy system module into a top-down representation of the macro economy, the scenarios can be analyzed both with respect to their technological and economic feasibility. In a second round of dialogues, stakeholders assessed the plausibility of the scenarios and identified potential socio-political externalities of the modelbased mitigation scenarios.

The outline is as follows. Section 2 presents the methodology. Section 3 discusses the outcomes of the participatory scenario definition process. Section 4 guides through the scenario results obtained with REMIND-D, focusing on structural trends in the development of CO_2 emissions by sector, modal splits in the freight and passenger transport sector and the electricity generation mix. Mitigation costs, along with a sensitivity analysis on how they depend on the stringency of the mitigation ambition, are presented in Section 4.4. Section 5 reports the CSO stakeholders' evaluations of the mitigation scenarios. Section 6 summarizes and concludes.

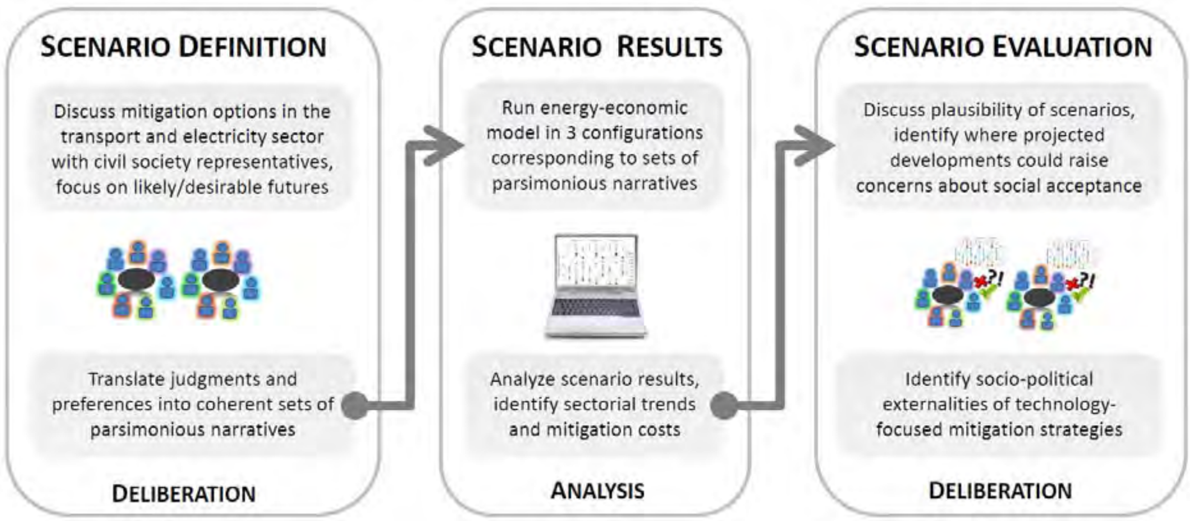

Figure 1: Stylized overview of the applied methodology.

2. Methodology

The objective of this research was to develop ambitious mitigation scenarios for Germany that integrate both techno-economic and socio-political dimensions of the domestic mitigation challenge. In order to achieve this, a participative scenario definition and evaluation process was conducted with CSO stakeholders from the transport and electricity sector. An outline of its organizational setup is presented in Schmid et al. (2011). Figure 1 gives an overview of the applied methodology.

2.1. Participatory scenario definition

Scenarios are a linking tool that integrates qualitative narratives and quantitative formulations based on formal modeling (Nakicenovic et al., 2000). In order to define scenarios, i.e. formalize the link between the two elements, "parsimonious narratives" have been established in the IAM community. They consist of contextual information on anticipated key future developments and corresponding quantitative projections for boundary conditions (Kriegler et al., 2010), and intend to convey substantive meaning to a particular set of boundary conditions for IAMs.

Several parsimonious narratives for key future developments in the transport and electricity sector were developed in collaboration with CSO stakeholders during two dedicated stakeholder dialogues. The 11 participants each come from environmental NGOs, industry and consumer associations, topic-related interest groups, urban planning, trade unions, transmission grid operators, the power generation and car manufacturing industry to renewable electricity providers. During these dialogues, selected mitigation options and associated key future developments were discussed with respect to direct and indirect implications and their perceived desirability. After each discussion, stimulated by an introductory question, a questionnaire elicited CSO stakeholders' positions for formal analysis.

The seven-point Likert-scale questionnaire (Likert, 1932) elicited judgments and preferences on possible future developments of key variables in the transport and electricity sector. For a number of possible developments, it asked to indicate whether its realization is perceived as likely or not, as well as desirable or not. Due to the small sample size, the data is not suited for econometric analysis. Instead, descriptive statistic measures of central tendency are employed. Mean, standard deviation, and mode give an indication of whether the perceptions of likely and desirable developments diverge and whether there is a degree of agreement across stakeholders. Along with the qualitative information obtained during the discussions as well as expert judgments from the literature, the elicited data serves as a basis for generating a set of parsimonious narratives on likely developments, and one on desirable developments in the transport and electricity sector. Finally, the modelling team translates these into corresponding input parameter configurations for the model REMIND-D.

2.2. The hybrid energy-economy model REMIND-D

REMIND-D is a Ramsey-type growth model that integrates a detailed bottom up energy system module, coupled by a hard link (Bauer et al., 2008). It facilitates an integrated analysis of the long-term interplay between technological mitigation options in the different sectors of the German energy system as well as general macroeconomic dynamics. A detailed description of REMIND-D is provided in Schmid et al. (2012). REMIND-D builds on the structural equations of the state-of-the-art IAM REMIND-R (Leimbach et al., 2010), which are reported in Bauer et al. (2011). The objective of REMIND-D is to maximize welfare, i.e. the intertemporal sum of discounted logarithmic per capita consumption.

In general all types of models, for example climate models, energy-system models or economic models, feature a strong reduction of complexity in comparison to the real world. They are stylized illustrations of the most important mechanisms of action which can be observed in reality. In order to solve a mathematic problem numerically, this approach is unavoidable. In this case of a coupled macroeconomic energy-system model certain underlying assumptions are made to achieve such a reduction of complexity. These assumptions are shortly outlined below. In macroeconomic modelling they are current praxis. In spite of the sometimes strongly simplifying assumptions, models help analyzing complex thought experiments which results are relevant in reality. Depending on the specific type of model, restrictions and strengths can vary as well as the question that could be answered.

An underlying assumption of the macroeconomic production function of Remind-D regards Germany as a closed economy without individual actors demanding or producing any commodities. The national GDP, produced from the three production factors capital, labor, and energy, has to cover the costs of energy systems and investment in the macroeconomic capital stock. The rest remains to increase welfare. Thereby the welfare of the whole society is being maximized, not only the GDP. There is one representative household and furthermore full employment is assumed. Of course these adoptions are not in accordance with reality; nevertheless they are necessary for optimization models. Restrictions resulting from this remain especially that Remind-D can neither analyze effects on employment of climate change policies nor does it consider the role of individual actors (companies or households) or the question of distribution. Moreover, the algorithm of optimization leads per se to more climate mitigation costs in ambitious scenarios of CO_2 emission reduction as it would be the case in less ambitious scenarios.

Strengths of the Remind-D model compared to other macroeconomic/energy-system models refer especially to the mechanism of optimization and furthermore to the endogen representation of the sectors in the energy system and macroeconomics. While not included in other models, Remind-D offers various mechanisms of feedback. Additionally the model allows an analysis of the long-term effects of investment decisions. Thereby the model results set a "benchmark" how a transformation, which generates optimal (maximal) societal welfare, could look like in the best case. Thus they are no prospects but projections, which are dependent of certain assumptions. According to German efforts on climate protection such indications are conceptually helpful. Consequently, statements can be made referring to the impact of different frame conditions in differing scenarios on the allocation of emission reduction on sectors of the energy system. Furthermore it can be shown which technologies could contribute to emission reduction and how a welfare-optimizing transformation could look like.

Mitigation is enforced by means of a strict emission budget of 16 Gt CO_2 over the time horizon of analysis, 2005-2050, resulting in roughly 85% emission reduction. The budget approach is inspired by the work of Meinshausen et al. (2009). When budgeting emissions, the model can choose annual emissions endogenously, allowing for exibility in the selection of mitigation options. In REMIND-D, future scarcities of energy carriers and CO_2 emissions are anticipated through shadow prices, implying perfect foresight. Hence, REMIND-D features optimal annual mitigation effort and technology deployment as a model output. Available mitigation options fall into four categories: (i) deploying alternative low-emission technologies, (ii) substituting final energy and energy service demands, (iv) improving energy efficiency, and (v) reducing demand. The latter is generally avoided by the model, as demand reductions have negative impact on GDP.

The energy system module of REMIND-D is endowed with a variety of alternative technologies that it may deploy endogenously. Endogenous capacity deployment is subject to potential and resource constraints for renewable primary energies, and fuel costs for fossil primary energies. The Carbon Capture and Sequestration (CCS) technology is available for the electrification and liquefaction of coal, lignite, gas and biomass. According to the decisions of the German Government, nuclear capacities are phased out until 2022. Domestic renewable energy potentials include lignocellulose, oily and sugar & starch biomass, manure, deep and near-surface geothermal, hydro, wind onshore, wind offshore, and solar irradiation. The model accounts for fluctuation of renewable electricity generation on short time scales explicitly via a residual load duration curve approach (Ueckerdt et al., 2011).

2.3. Participatory Scenario Evaluation

In the second round of stakeholder dialogues, the same CSO stakeholders evaluated the mitigation scenarios obtained with REMIND-D by discussing their plausibility and identifying where projected developments could raise concerns about social acceptance. The objective was to characterize critical socio-political externalities of technology-focused mitigation pathways. A better understanding of how goals of climate protection and energy security may conflict with those of an affordable energy supply for everybody and how these trade-offs can be tackled, is essential for transforming Germany towards a low-carbon energy future.

3. Scenario Definition

As outlined in Section 2.1, the development of parsimonious narratives, consisting of contextual information on anticipated key future developments and corresponding quantitative projections for boundary conditions, is central to this scenario definition process. Three scenarios emerged. The 'continuation' scenario enforces a set of parsimonious narratives in the transport and electricity sector that are deemed likely by CSO stakeholders. The 'paradigm shift' scenario reproduces a set of parsimonious narratives perceived as desirable by the majority of CSO stakeholders. A variant of the latter, the 'paradigm shift+' scenario, additionally allows for the deployment of several technological mitigation options, which the stakeholders judged as undesirable or discussed controversially. Yet, these technologies, e.g. CCS, are often favored by engineers. Along the lines of the discussion questions raised during the stakeholder dialogues, the different parsimonious narratives are elaborated in the following.

Table 1: Selected results of the Likert-Scale questionnaire of the CSO stakeholder dialogue on the transport sector. All statements relate to the time horizon until 2050. 1 indicates disagreement, 4 neutrality, and 7 agreement. STD = Standard Deviation, MS = Modal Split, MIT = Motorized Individual Transport, PT = Public Transport

	Likely			Desirable		
Future Development	Mean	STD	Mode	Mean	STD	Mode
Annual t-km truck increases	6.55	0.69	7	3.09	2.25	1
Shift t-km from road to rail	3.73	1.74	3	6.09	1.38	7
Decouple freight&GDP growth	4.09	1.3	3/4	5.90	1.87	7
MS MIT decreases to $\leq$ 50%	3.91	1.64	3/5	4.73	2.28	7
MS PT increases significantly	3.64	1.75	5	5.64	1.63	7
MS cycling&walking increases	4.55	2.07	2/7	5.64	1.97	7
Bioethanol $\geq$ 50% share	3.33	1.55	2	3.33	2.33	1
Biodiesel $\geq$ 50% share	3.33	1.79	3/5	3.33	2.33	1
Hydrogen dominant fuel	3.55	1.92	3	3.64	1.45	3

Is an increase of total annual freight mileage unavoidable? Historically, freight transportation and GDP growth rates correlated strongly, however, their causal relationship is not straightforward (Feige, 2007). As indicated in Table 1, decoupling freight and GDP growth rates by reducing annual truck mileage and shifting freight from road to rail is perceived as a desirable mitigation option by CSO stakeholders. Yet, they anticipate annual ton-km (t-km) mileage with fossil-fuel based trucks to increase continuously until 2050. This scenario is corroborated by expert judgments. Lenz et al. (2010), e.g., predict a dramatic increase in diesel truck mileage from 466 Bn t-km in 2005 to 787 Bn t-km in 2030, constituting a severe carbon lock-in. In the 'continuation' scenario, this trend is enforced by an exogenous linear increase of annual freight transport with trucks up to 787 Bn t-km in 2050, as a conservative estimate. Howsoever, the CSO stakeholders strongly advocated policy efforts directed at reducing total transport mileage and achieve a shift from road to rail. They claim that viable solutions exist, but lack of political will impedes their implementation. Holzhey (2010) finds that a doubling of freight transport with rail in Germany until 2030 is technically possible, even though concerted investments are required. Consequently, in the two 'paradigm shift' scenarios, it is assumed that freight transport and GDP growth can be decoupled in the future.

Is multi-modality a viable option for decarbonizing the passenger transport sector? The modal split in the passenger transport sector is heavily biased towards motorized individual transport (MIT) with cars, accounting for roughly 80% of travelled person-km (p-km) annually (BMVBS, 2008). CSO stakeholders expect MIT to remain the dominant mode of transportation in the future. Hence, the 'continuation' scenario is bound to a share of 80%

MIT in modal split annually. However, CSO stakeholders perceive a structural change in the modal split as a desirable future development, seeing some potential for public transport (PT), and also non-motorized short distance transport to increase, e.g. by means of a fast bicycle lane network. CSO stakeholders particularly stress the importance of increasing infrastructure investments for PT to enable multi-modality transport patterns, supporting the proposals of the European Commission's white paper on transport (EC, 2011). By prescribing an increase in the share of PT in the modal split for both short and long distance passenger transport, these developments are reproduced in the two 'paradigm shift' scenarios.

Which alternative low-carbon fuels ought to be dominant in the future? Instead of a shift in the mode of transportation, less carbon-intensive fuels for conventional vehicles are another technological mitigation option. CSO stakeholders are controversial about the desirability of first-generation biofuels and doubt that second-generation biofuel technologies (e.g. biofuels from lignocellulose) will be available in large scale. Likewise they doubted the technological feasibility of a hydrogen future (e.g. Fischedick et al., 2005), exploiting overproduction of REG capacities via electrolysis. Since the desirability of these technological options was contested, they are available to the model only in the 'paradigm shift+' scenario.

Are landscape externalities of renewable electricity generation (REG) capacities and transmission lines problematic, and what are potential remedies? A concomitant effect of large-scale deployment of REG and transmission line (TL) capacities is that they technologize the landscape. This landscape externality was in fact considered problematic with regard to social acceptance. Especially biogas electrification, accompanied by large corn monocultures were judged as unacceptable, see Table 2. CSO stakeholders expect that substantial TL extensions, necessary to distribute and balance fluctuating REG, are potentially impeded due to local resistance. However, they find it desirable that such local oppositions are resolved and encourage that REG technologies, with the exception of biogas electrification, constitute a very large share of the electricity mix in the future. Possible remedies for fostering social acceptance towards REG and TL capacities include procedural justice and increased participation and ownership by the local population (Musall and Kuik, 2011; Zoellner et al., 2008). To represent the effect of a certain degree of social refusal towards large-scale REG and transmission line deployment in REMIND-D, the REG potentials in the 'continuation' scenario are lower than in both 'paradigm shift' scenarios.

Which energy efficiency growth rate is feasible and what is the role of the rebound effect? It is widely agreed that energy efficiency improvements are an important mitigation option in Germany, especially for the electricity sector.

Table 2: Selected results of the Likert-Scale questionnaire of the CSO stakeholder dialogue on the electricity sector. All statements relate to the time horizon until 2050. 1 indicates disagreement, 4 neutrality, and 7 agreement. STD = Standard Deviation, TL = Transmission Lines, IND = Industry, HHS = Households, PP = Power Plant, CCS = Carbon Capture and Sequestration.

	Likely			Desirable		
Future Development	Mean	STD	Mode	Mean	STD	Mode
Local resistance impedes TL	3.57	1.40	2/3/5	1.46	0.66	1
Deploy heavily wind offshore	5.64	1.34	5	4.92	1.89	7
Deploy heavily biogas plants	4.21	1.25	5	3	1.63	2
Elec. demand IND decreases	4.71	1.86	6	4.77	1.94	4/6/7
Elec. demand HHS decreases	4.07	1.90	3	5.07	2.10	7
Rebound effect compensates	5.14	1.35	5	2.92	1.55	1/3/4
Increase Gas PP next decade	5.43	1.16	5	5.54	2.03	6
Decommission existing Coal PP	4.36	1.55	5	5.23	2.24	7
Large scale availability CCS	3.54	1.94	1/4	3.58	2.35	1

Yet CSO stakeholders expect electricity demand to remain stable or increase in the future, despite judging high efficiency growth rates as a desirable development. Here, the rebound effect is likely to prove itself as a real obstacle. It postulates that even though individual appliances are more energy efficient, the total energy demand increases due to an increase in the total number of appliances (e.g. Sorrell et al., 2009). In order to translate these judgments, efficiency growth rates of the final energy demand perpetuate historical trends in the 'continuation scenario', averaging 0.5 % annually. The two 'paradigm shift' scenarios assume significant improvements and the exogenous efficiency growth rates of final energy demand amount to an average of 2.3 % annually.

Which thermal electricity generation capacities are acceptable in the next decades? Due to the phase-out of nuclear until 2022, these generation capacities need to be replaced within the next decade.

Table 3: Summary overview of the model constraints that define the three scenarios, resulting from the participatory process. FT = Freight Transport, PT = Public Transport, MS = Modal Split, REG = Renewable Electricity Generation, PP = Power Plant, CCS = Carbon Capture and Sequestration.

Model Constraint	Continuation	Paradigm Shift	Paradigm Shift+
Decoupling FT&GDP	no	yes	yes
PT share in MS	constant	increase	increase
REG potential	medium	high	high
Energy efficiency	medium	high	high
Decommission Coal PP	no	yes	yes
CCS by 2025	no	no	yes
Biofuel potential	low	low	high

CSO stakeholders oppose the built-up of new CO_2 emission intensive coal power plants. Instead, they consider it both likely and desirable to deploy gas power plants, which are not only less CO_2 intensive, but are also better capable of balancing fluctuating REG (dena, 2010). 47% of total German CO_2 emissions in 2010 were incurred by lignite and hard coal power plants. The option of decommissioning them before the end of their techno-economic lifetime, and replacing them with REG capacities, albeit hardly discussed, constitutes an effective mitigation option. Even though CSO stakeholders judged this option as desirable, they consider it as moderately realistic. To simulate a carbon lock-in from persistent coal electrification, existing hard coal and lignite power plants are subject to a must-run constraint in the 'continuation' scenario. This must-run constraint implies that the coal power plants may not be put out of service before the end of their technical lifetime. A large-scale deployment of the CCS technology was judged as neither particularly likely nor desirable and is hence available to the model only in the 'paradigm shift+' scenario, from 2025 onwards.

Table 3 summarizes the model constraints defining the three scenarios.

4. Scenario Results

The model REMIND-D finds an optimal solution for each of the scenario configurations, despite the strict emission budget of 16 Gt CO_2. All scenarios achieve 85% CO_2 emission reduction in 2050 relative to 1990, corroborating the finding that ambitious domestic mitigation in Germany is technically feasible. Yet, the scenario results in the following Sections indicate that a continuation of historical trends in the freight and electricity sector, deemed likely, leads to a carbon lock-in that renders ambitious mitigation extremely challenging.

4.1. CO_2 Emissions by Sector

Mitigation shares of the three sectors transport, electricity and heat structurally differ across scenarios, as illustrated in Figure 2. The y-axis measures annual CO_2 emissions in Mt CO_2, whereas the x-axis displays the three sectors for each scenario. Time is indicated by color coding. First, Figure 2 visualizes the structure of the sectorial relationships in one scenario, highlighted by the connecting lines in the years 2005, 2020 and 2050. Second, the sectorial trends over time can be compared across scenarios. And third, it emphasizes the speed of the transformation: the larger the white areas are within a bar, the faster is the CO_2 emission reduction between two time steps. CO_2 emission reductions between 2005 and 2015 are similar in all scenarios - a fast decrease of emissions of 29-32% in the electricity sector, 29-32% in the industrial, residential and commercial heat sectors, and 4-9% reduction in the transport sector. From 2015 onwards, there are structural differences between the developments in the 'continuation' and both 'paradigm shift' scenarios. The speed of emission reduction in the electricity sector stagnates in the 'continuation' scenario, due to the must-run constraint for the existing lignite and hard coal power plants. Additional committed emissions in the 'continuation' scenario stem from the prescribed increase in freight transport with trucks.

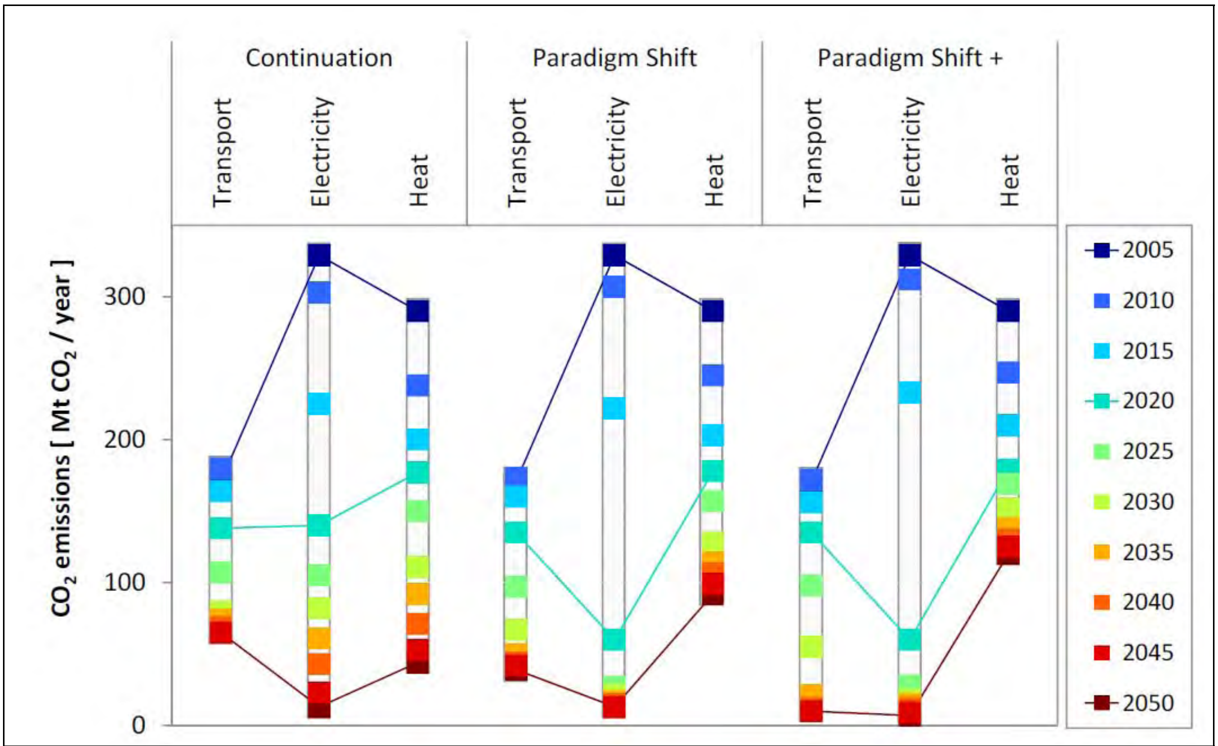

Figure 2: Annual CO_2 emissions from energy in Germany for 2005-2050 in Mt per year, by scenario and sector. These model results are obtained with REMIND-D.

The total carbon lock-in over the time horizon of analysis, 2005-2050, amounts to 6.15 Gt CO_2 from coal electrification and 2.67 Gt CO_2 from fossil-fuel based freight transport. In sum, these 8.8 Gt CO_2 deplete 55% of the total emission budget. Consequently, the heat sector needs to deliver a substantially higher mitigation effort in the 'continuation' scenario than in the two 'paradigm shift', in order to meet the total CO_2 emission budget. In the two 'paradigm shift' scenarios, the electricity sector decreases CO_2 emissions much faster, delivering a reduction of 80% between 2005 and 2020. Therefore, more CO_2 emissions can be incurred in the heat sector, providing process heat for industry and residential heating. This structural effect is even more pronounced in the 'paradigm shift+' scenario; here the availability of new low-carbon technologies leads to an almost complete decarbonization of the freight and electricity sectors by 2035. These findings illustrate the advantage of an integrated approach to mitigation modelling, allowing for an analysis of the interplay between different sectors.

4.2. Transport Sector

Until 2050, total CO_2 emissions within the transport sector decrease by 47% in the 'continuation', 73% in the 'paradigm shift' and 93% in the 'paradigm shift+' scenario versus 2005. The majority of annual reductions are achieved during the next two decades, yet the drivers differ across the three scenarios. Clear structural breaks emerge in both modal splits in the two 'paradigm shift' scenarios.

In all scenarios, freight transport by inland water navigation remains constant, as illustrated by Figure 3. In the 'continuation' scenario, freight train capacities also remain at today's levels, however, freight transport with trucks increases continuously, as enforced by the scenario assumption of coupled GDP and freight transport growth rates. As a consequence, the freight sector's annual emissions remain constant at 60-70 Mt CO_2, as the availability of alternative low-emission fuels is limited in this scenario. These committed emissions are avoided in both 'paradigm shift' scenarios. Here, the decoupling indicator (t-km/GDP) does not increase by 20% from 2005 to 2050, but decreases by 20% and 10% respectively. Apart from keeping freight transport mileage constant at today's level, through a restructuring the economic system towards less transport-intensive value chains, mitigation is enabled by massive rail infrastructure expansions allowing for train mileage to tripe until 2030. In the 'paradigm shift+' scenario, the truck mileage remains at higher levels than in the 'paradigm shift' scenario, due to the availability of alternative low emission fuel technologies, e.g. second generation biofuels and liquefaction of lignite in combination with the CCS technology. Annual per capita passenger transport decreases from 13,000 km in 2005 to 11,000 km in the year 2050 in both 'paradigm shift' scenarios; the parsimonious narrative foresees that one part of the difference will be substituted by non-motorized traffic, i.e. cycling and walking. In the 'continuation' scenario, however, the per capita p-km are forced to decrease down to 9000 p-km in 2050, due to mitigation pressure induced by the carbon lock-in in the freight and electricity sector.

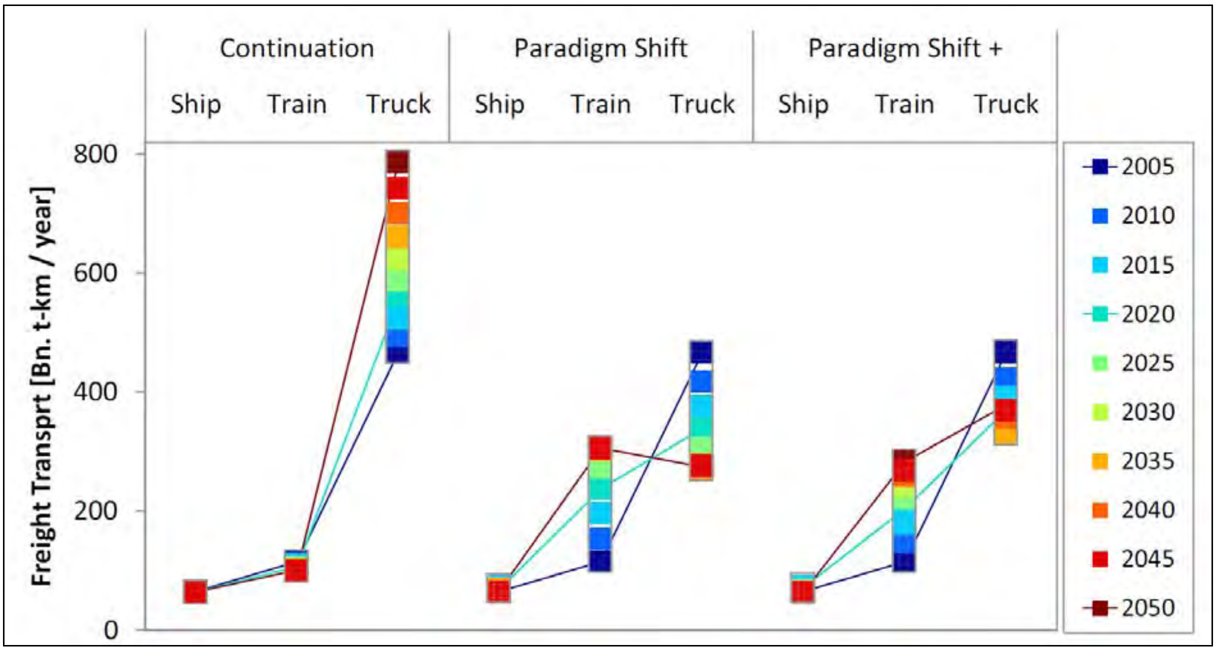

Figure 3: Annual freight transport mileage for 2005-2050 in Bn ton-km (t-km) per year, by scenario and mode. These model results are obtained with REMIND-D.

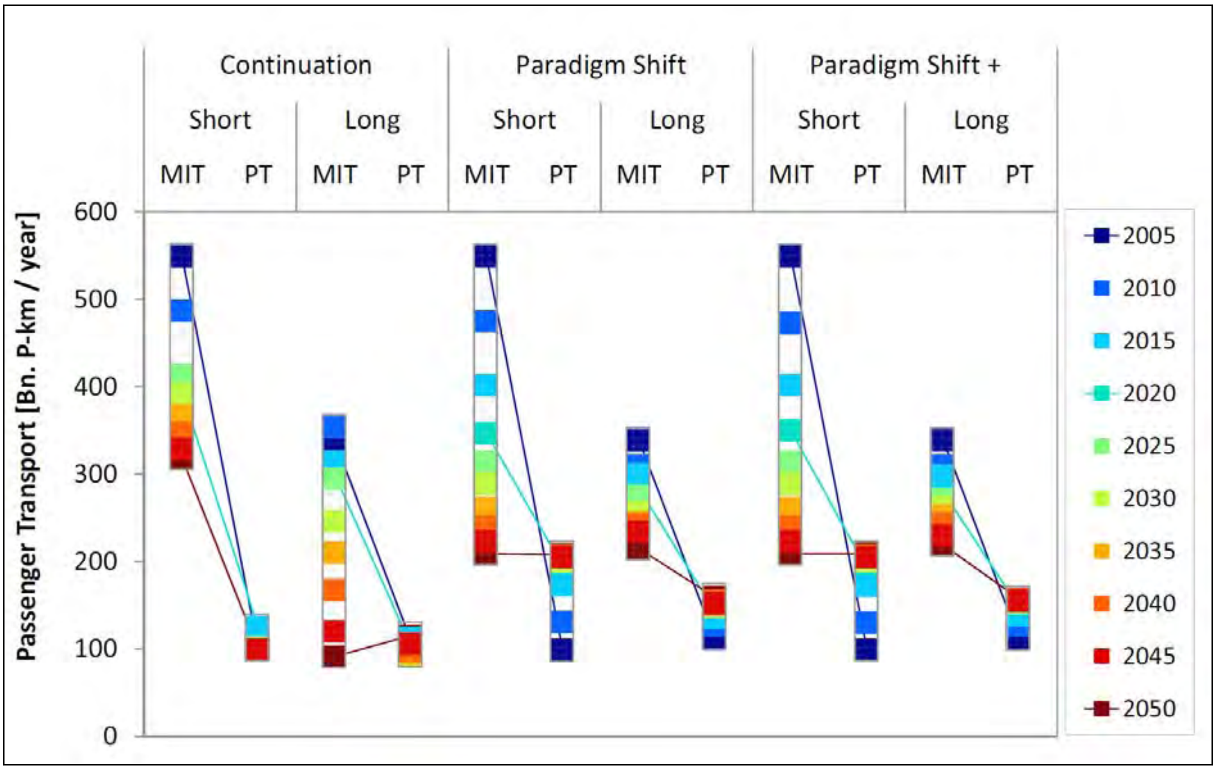

Figure 4: Annual passenger transport mileage for 2005-2050 in Bn passenger-km (p-km) per year, by scenario and mode. These model results are obtained with REMIND-D. MIT = Motorized Individual Transport, PT = Public Transport

The total annual p-km by transport mode for each scenario are illustrated in Figure 4. Here, the structural change in both 'paradigm shift' scenarios becomes evident: MIT decreases at a decreasing rate until 2050 and PT steadily increases until 2020, remaining constant thereafter. Hybrid buses, electrified light rail and regional trains deliver additional short distance PT. Together, they account for roughly 50% of the modal split of short distance transport in 2050. Incremental long distance PT will be delivered with electric trains. In all scenarios, anticipated carbon budget restrictions and implicit carbon pricing make conventionally fuelled cars too expensive to operate, so they are phased out entirely until 2030. Diesel cars, predominantly suitable for long distance driving, are first substituted by diesel hybrids and then by hybrid gas cars in all scenarios. Petrol cars are replaced with hybrid-plug in gasoline cars, which are electric cars with a petrol-fuelled rage extender. In the 'paradigm shift+' scenario, they are partly replaced with hydrogen hybrid cars, as hydrogen is produced from lignocelluloses with CCS here, with the ability to extract CO_2 from the atmosphere and producing de-facto "negative" CO_2 emissions. In all scenarios, there is a trend to gradually electrify the transport sector, with the total demand of electricity for transport increasing by several orders of magnitude until 2050, yet never exceeding 15% of total electricity production.

4.3. Electricity Sector

The aggregated technology mix of the electricity sector for the three scenarios is illustrated in Figure 5. In the two 'paradigm shift' scenarios, where the model is given the option to decommission existing hard coal and lignite power plants from 2015 onwards, these capacities are shut down by 2020. They are temporarily replaced by gas turbines, about 25 GW of capacity are built between 2015 and 2020. Once enough REG capacity is installed, the gas turbines go out of service again in both 'paradigm shift' scenarios by 2030. In the 'continuation' scenario, there is no such temporary increase in gas capacities, as existing coal and lignite power plants continue to produce electricity. In all scenarios, REG is rapidly expanded and doubling over the next five years.

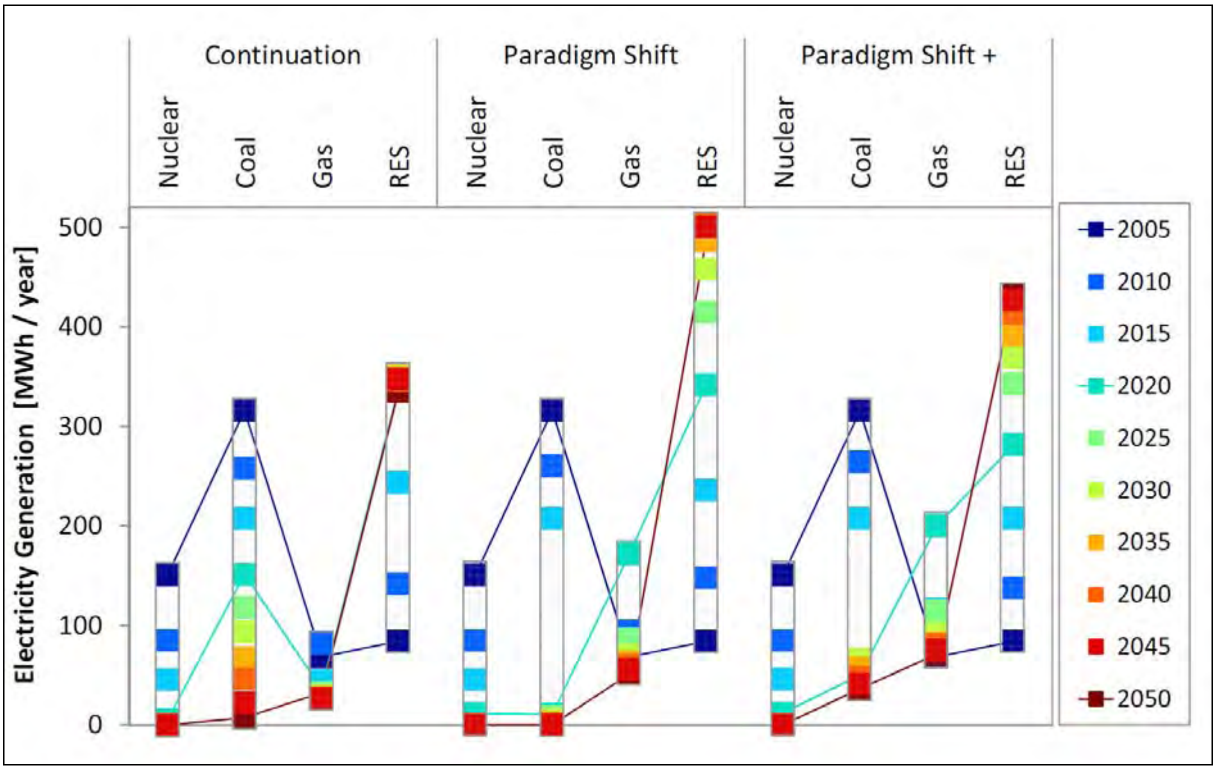

Figure 5: Annual electricity generation for 2005-2050 in MWh per year, by scenario and aggregated technologies. These model results are obtained with REMIND-D.

From 2020 onwards, the installed REG capacities stagnate in the 'continuation' scenario. This is due to the moderate potential in the scenario definition, motivated by a restrictive public attitude that constrains the incremental deployment of RE capacities and transmission lines. Total electricity production is forced to decrease from 620 MWh in 2005 to 375 MWh. Because of the carbon lock-in from freight transport and coal electrification, the model cannot afford to allocate more CO_2 from the emission budget to the electricity sector for covering gas turbines. These could provide more balancing capacities so solar potentials could be fully exploited, which is not the case in the 'continuation' scenario. Instead, REMIND-D opts for the least attractive mitigation option: imposing electricity demand reductions in all sectors, including industry. A consequence of this is a reduction in GDP growth.

In both 'paradigm shift' scenarios, REG capacities continuously expand, especially offshore wind, and total electricity production stabilizes between 530 and 560 MWh. The slightly reduced demand is due to high efficiency growth rates. In 2050, onshore wind capacities reach a maximum of 100 GW in both 'paradigm shift' scenarios. Offshore capacities reach 150 GW in the 'paradigm shift' scenario and 180 GW in the 'paradigm shift+' scenario. Geothermal electricity production also plays a vital role in all scenarios with 20-35 GW installed capacity. REMIND-D installs 110 GW of solar photovoltaic in the 'continuation' scenario by 2050. In the 'paradigm shift' scenarios, other less expensive technologies, e.g. wind onshore and offshore, provide sufficient electricity generation potential and solar photovoltaic plays only a minor role. Biomass electrification plays a subordinate role in all scenarios as REMIND-D prefers to use all available biomass for fuel production. In the 'paradigm shift+' scenario, 14 GW of lignite power plants with the Oxyfuel CCS technology are installed, as well as 25 GW of natural gas combined cycle plants with CCS. When compared to the 'paradigm shift' scenarios, these capacities somewhat reduce the need for REG capacities.

4.4. Mitigation Costs

Comparing the results of two scenarios that differ with respect to the emission constraint only, allows for determining the differential effects of mitigation enforcement. One measure of economic mitigation costs is the cumulative difference in discounted GDP losses (referred to as cumulative GDP losses hereafter), between two scenario runs that have the same restrictions, except for the size of the CO_2 emission budget. Macroeconomic mitigation costs in terms of cumulative GDP losses for the 'continuation', 'paradigm shift' and 'paradigm shift+' scenario amount to 3.5%, 1.4% and 0.8% between 2005 and 2050. The respective reference case with a larger carbon budget leads to moderate 40-45% CO_2 emission reduction in 2050 relative to 1990. Figure 6 illustrates how cumulative GDP losses between scenarios diverge with increasingly strict carbon budgets. For ease of interpretation, the x-axis displays the respective % of CO_2 emission reduction achieved in 2050 relative to 1990. For moderate mitigation targets up to 65% CO_2 emission reduction in 2050, GDP losses remain below 0.5% in all scenarios. Mitigation costs in this order of magnitude are also found by global IAM analyses (e.g. Edenhofer et al., 2010; Luderer et al., 2012).

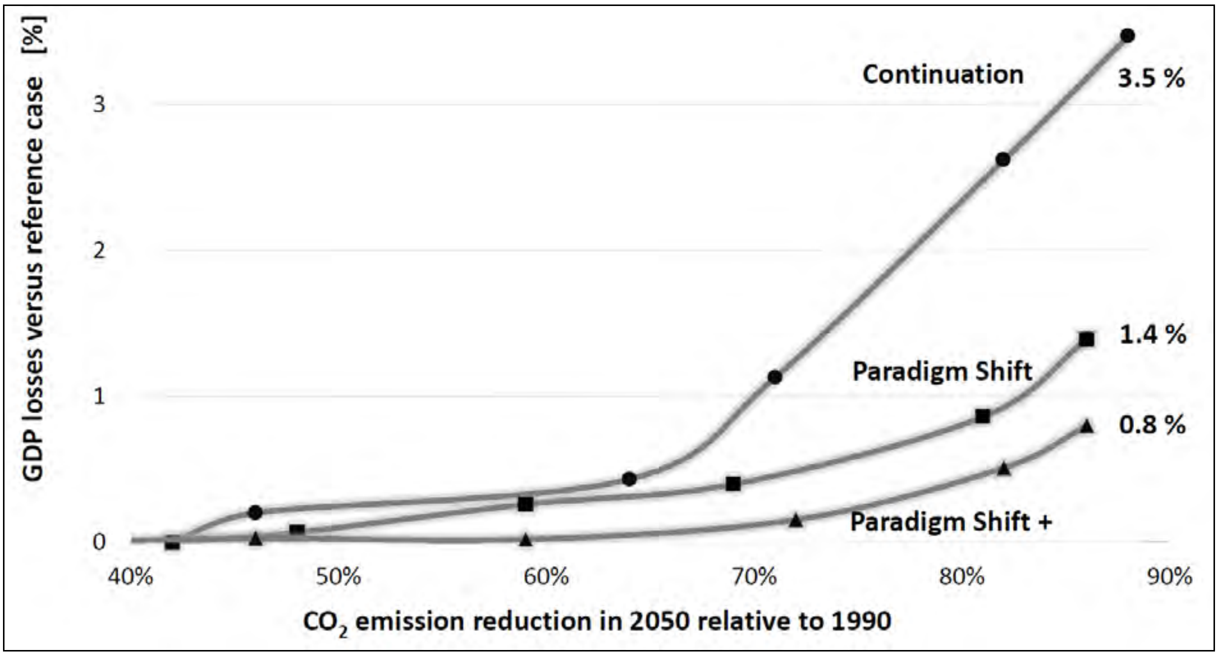

Figure 6: Mitigation cost curve for the three scenarios, in terms of cumulative discounted GDP losses compared to a respective reference scenario with 40-45% CO_2 emission reduction in 2050. These model results are obtained with REMIND-D.

However, for more ambitious targets, the mitigation costs in the 'continuation' scenario increase relatively faster than in the two 'paradigm shift' scenarios. This divergence is induced through the differences in scenario assumptions.

The main drivers for increasing GDP losses in the 'continuation' scenario are moderate efficiency growth rates and endogenously enforced demand reductions due to the aforementioned carbon lock-in in the freight and electricity sector. GDP losses remain significantly lower for all mitigation targets in the 'paradigm shift' scenario. Higher efficiency growth rates in all sectors of the economy, larger REG potential and the option to avoid the carbon lock-in are responsible for this. In terms of the underlying parsimonious narratives, the results indicate that ambitious mitigation in Germany can be achieved at relatively lower costs if structural changes in modal splits of the freight and passenger transportation sector and a fast decarbonization of the electricity sector are pursued. Mitigation costs in the 'paradigm shift+' scenario remain even lower for all levels of mitigation ambition. This is due to additionally available technological mitigation options in the form of CCS and larger biofuel potentials. Yet the incremental effect is not as decisive as moving from the 'continuation' to the 'paradigm shift' scenario.

5. Scenario Evaluation

CSO stakeholders perceive three projected developments in the 'continuation' scenario as implausible, due to socio-political externalities that conflict with other policy arenas. First, the model results indicate a strong decrease of motorized individual transport that is not compensated for by more public transport mileage. Massive state intervention would be necessary to induce behavioral changes of such magnitude, e.g. through carbon pricing policies entailing prohibitively high transport costs. In such a world, individual mobility would become a luxury good. The CSO stakeholders assess that such policies will lack social acceptance and strongly emphasize the value of individual mobility in modern societies. Second, the required electricity and heat demand reductions are considered as politically not enforceable in reality. To induce such a development, again, rigorous carbon pricing policies would be required, which would increase the price of electricity and heating. Several stakeholders pointed out the dangers of energy poverty if any such mitigation policy is not accompanied by effective redistribution schemes. Third, the CSO stakeholders doubt that the projected CO_2 emission reductions and efficiency improvements in the heat sector can be realized, seeing institutional barriers as for example the well-known landlord-tenant conflict of responsibility. In sum, these critical socio-political externalities motivated the CSO stakeholders to assess the 'continuation' scenario as highly undesirable, despite the fact that it reaches the required mitigation target. Yet they reconfirmed the likeliness of its projected developments in the freight transport and electricity sector, leading to a lock-in into current behavior and carbon-intensive infrastructure. In consequence, they conclude that, if the carbon lock-in becomes reality, ambitious mitigation targets will be out of reach.

The 'paradigm shift' scenarios see the carbon lock-in resolved. CSO stakeholders prefer the 'paradigm shift' scenario over the 'paradigm shift+' scenario as they predict substantial public protest against the large-scale deployment of CCS infrastructure and biofuel production. They argue that the incremental effect on decreasing mitigation costs may not outweigh the direct and indirect costs of public protest. CSO stakeholders articulated several concerns for policies that aim at inducing the structural breaks from historical trends inherent to the 'paradigm shift' scenario. The quality of public transport services needs to increase significantly, both in urban environments and in rural areas. Inter alia, this would require a redirection of infrastructure investments from road to rail, an issue considered long overdue by the CSO stakeholders. Furthermore, they raised concerns regarding the projected rapid decommissioning of existing coal power plants, as it may entail increasing regional unemployment rates in Germany's structurally weak lignite mining areas. Finally, CSO stakeholders considered a fast deployment of renewable electricity generation and transmission line capacities as socially acceptable - if procedural justice is high throughout the process. This however implies transparent planning and installation as well as institutionalized possibilities for local communities to participate. In order to deliver, the different policy arenas need to become more intertwined and resolve their conflicting goals.

6. Summary and Conclusion

This paper presents three model-based mitigation scenarios for Germany that achieve 85% CO_2 emission reduction in 2050 relative to 1990. These scenarios were defined and evaluated in a participatory process with CSO stakeholders from the transport and electricity sector. During dialogues, their preferences on future mitigation options were discussed and elicited. Along with findings from the literature, the input from the CSO stakeholders built the basis to generate parsimonious narratives on possible future developments of key variables in the transport and electricity sector.

The 'continuation' scenario is characterized by a set of developments that are deemed highly likely by all participants. These include the dominance of motorized individual transport, unabated coal electrification, moderate energy efficiency growth rates, local resistance against windmills and transmission lines as well as the continuation of coupled freight transport and GDP growth rates. Already coal electrification and fossil-fuel based freight transport mileage induce 8.8 Gt CO_2 of committed emissions. This carbon lock-in accounts for 55% of the total CO_2 emission budget over the time horizon of analysis, from 2005 to 2050. As a consequence, non-technical mitigation options slowing down economic growth are exploited by REMIND-D for meeting the budget constraint. These include significant energy service demand reductions in passenger transportation as well as final energy demand reductions for electricity and the provision of heat. Additionally bound to moderate energy efficiency improvements, the 'continuation' scenario exhibits mitigation costs of 3.5 % cumulative GDP losses over the period 2005-2050, as compared to a reference case that achieves 40% CO_2 emission reduction in 2050 relative to 1990.

The two 'paradigm shift' scenarios reproduce future developments judged as desirable by participating stakeholders. These include a decrease in total freight transport mileage, a shift in the modal split of freight transport sector from road to rail, a substantial increase of public and non-motorized transport in the modal split of passenger transportation, a phase-out of conventional coal electrification until 2020, a rapid and large-scale deployment of renewable electricity generation and transmission line capacities as well as a fourfold increase in energy efficiency growth rates. REMIND-D immediately exploits these mitigation options whereby mitigation costs decrease by more than half when compared to the 'continuation' scenario, with 1.4 % of cumulative GDP losses. The 'paradigm shift+' scenario, which additionally allows for the use of CCS and large-scale biofuel production, achieves even lower mitigation costs of 0.8 %. However, CSO stakeholders remain skeptical whether these technologies are feasible in large scale, also due to social refusal. Thus the following conclusions can be drawn.

- Model results corroborate that achieving an ambitious mitigation target of 85% German CO_2 emission reduction by 2050, relative to 1990, is technically feasible. However, this research unravels that critical socio-political externalities may pose a significant barrier to ambitious domestic mitigation.
- Deliberative stakeholder dialogues reveal strong discrepancies between likely and desirable future developments in the transport and electricity sector. Increasing fossil-fuel based freight mileage and the continuous electrification of coal, deemed likely but not desirable, will lead a cumulative carbon lock-in of 8.8 Gt CO_2 until 2050, accounting for 55% of the total CO_2 emission budget.
- Model results indicate that enforcing ambitious mitigation targets in the face of this carbon lock-in leads economic growth to slow down and bears severe socio-political externalities. To overcome these trade-offs, the carbon lock-in has to be avoided and, additionally, energy efficiency and renewable deployment growth rates have to increase.
- Participating stakeholders point out that in order to resolve the carbon lock-in, major paradigm shifts are needed, which in turn require concerted political as much as societal will.

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