Originally published as:

Schmid, E., Knopf, B. (2012): Ambitious mitigation scenarios for Germany: A participatory approach. - Energy Policy, 51, 662-672

DOI: 10.1016/j.enpol.2012.09.007

Ambitious Mitigation Scenarios for Germany: A Participatory Approach

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Abstract

This paper addresses the challenge of engaging civil society stakeholders in the development process of ambitious mitigation scenarios that are based on formal energy system modeling, which allows for the explicit attachment of normative considerations to technology-focused mitigation options. It presents the definition and model results for a set of mitigation scenarios for Germany that achieve 85% CO_2 emission reduction in 2050 relative to 1990. During consecutive dialogues, 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 with regard to plausibility and social acceptance implications. Even though the limited scope of this research impedes inferential conclusions on the German energy transition as a whole, it demonstrates that the technological solutions to the mitigation problem proposed by the model give rise to significant societal and political implications that deem at least as challenging as the mere engineering aspects of innovative technologies. These insights underline the importance of comprehending mitigation of energy-related CO_2 emissions as a socio-technical transition embedded in a political context.

Keywords: Social Acceptance, Stakeholder Dialogue, Energy System Modelling

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June 11, 2012

1. Introduction

Ambitious domestic mitigation efforts by Annex I 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 by 2020. In the long-term, the German Government endorses an ambitious target of 80-95% energy system related CO_2 emission reduction by 2050 relative to 1990 (Federal Government, 2010). Model-based mitigation scenarios that indicate how this transformation can be accomplished are a frequently demanded form of scientific policy advice.

As energy system modeling has traditionally been the domain of experts, particularly engineers, existing mitigation scenarios frame mitigation largely as a technology problem that can be solved by switching to innovative low-carbon technologies. For Germany, several model-based scenario studies have demonstrated that achieving the Government's long-term mitigation target will be technically feasible if best available technologies penetrate the market in large scale (e.g. Schlesinger et al., 2010; Nitsch and Wenzl, 2009; Nitsch et al., 2010; Kirchner et al., 2009). To achieve this, the studies suggest rigorous energy policy measures with far-reaching implications for the German society.

However, it was not subject of the analysis in these scenario studies whether their projected developments align with societal preferences. In case they do not align, social refusal to adopt or allow for the adoption of low carbon technologies may challenge ambitious mitigation targets. Indications that this is a real challenge in Germany are already observed. Local protest against the exploration of carbon sequestration sites contribute to the paralysis in the policy process for passing European legislation on carbon sequestration. Widespread refusal to use petrol with 10% biofuel additive (E10) endangers Germany's fulfillment of the European biofuel quota (MWV, 2011). Local opposition against the construction of new power plants is considered as the most important market entry barrier for utilities (Deloitte, 2011). Further, local opposition against onshore wind farms, due to e.g. negative landscape externalities (Meyerhoff et al., 2010), have resulted in 40 negative out of 61 community referendums between 2009 and 2012 (Löhle, 2012).

Since public or local oppositions and other acts of societal 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. Often, social acceptance is understood as something that can be established ex-post to investment or policy decisions by providing sufficient information to the public (e.g. Federal Government, 2010). However, attempts to explain acceptance and opposition in literature increasingly resort to procedural and institutional factors like beliefs, concern, place attachment, perceived fairness and levels of trust (Devine-Wright, 2008) which cannot be mediated by mere information campaigns. Rayner (2010) argues that the process of how a society chooses an energy future itself is as important for a socially, politically, economically and environmentally sustainable outcome as the availability of low-carbon technology options.

The Ethics Commission for a Safe Energy Supply, appointed by the Federal Government, corroborates that in order to ensure a high level of societal acceptance for the energy supply, transparency in the decisions made by both parliament and government as well as participation by societal groups in the decision-making process is a prerequisite (Ethics Commission for a Safe Energy Supply, 2011). Due to the decisive role that model-based mitigation scenarios can play as a form of scientific policy advice, the call for transparency and participation in their design and development process is valid accordingly. A further convincing argument for engaging societal groups that have a stake in energy system developments is that the choice of low-carbon technologies requires a wide range of normative considerations and value judgments for which science alone does not have a mandate.

For taking into account societal preferences, the German Academies of Sciences advocate the application of 'analytical-deliberative' approaches (Renn et al., 2011) which originate in the field of risk management (e.g. Stern and Fineberg, 1996; Renn, 1999). Their notable trait is to provide a recursive linkage between the two discrete processes of analysis, the use of replicable methods developed by experts, and deliberation, the thoughtful weighting of options. 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. In order to develop model-based mitigation scenarios that explicitly take into account stakeholders' judgments and preferences, they 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 implications of technology-focused mitigation options. 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 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 no contemporary applications of participatory approaches to developing ambitious mitigation scenarios for Germany.

This paper aims to contribute in filling the gap by exploring a methodology for developing a set of model-based, long-term mitigation scenarios for Germany that are defined 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). Due to the pilot project character, the scenario results are to be interpreted as indicative of trends rather than being representative for the German civil society as a whole.

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., 2012a). 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 evaluated the plausibility of the scenarios and identified potential socio-political implications of the model-based 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.

2. Methodology

The objective of this research is to develop ambitious mitigation scenarios for Germany that integrate both techno-economic and socio-political dimensions of the domestic mitigation challenge. In order to build a bridge between

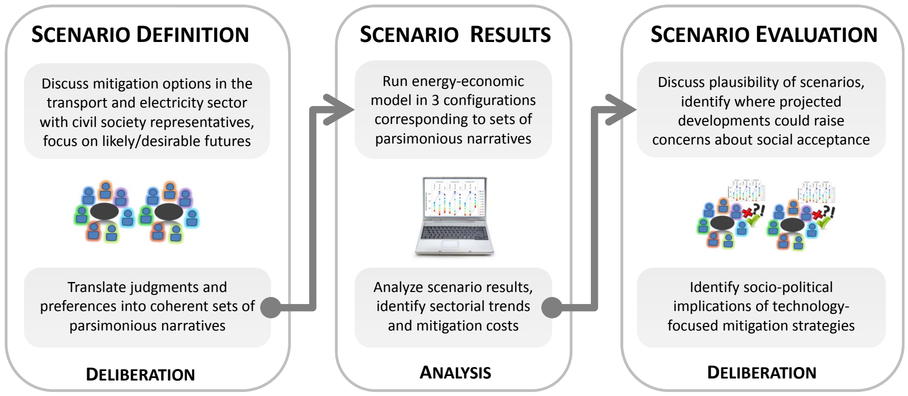

Figure 1: Stylized overview of the applied methodology

the two, the specific requirements on the research team go beyond pure expertise on energy-economy modeling and call for project partners that are well embedded in the civil society sphere. Thus, the core research team consisted of both non-governmental organization (NGO) partners and researchers that collaborated closely throughout the project. The participatory scenario definition and evaluation process illustrated in this paper was preceded by an intense preparatory phase in which the interdisciplinary research team developed a joint understanding of how stylized model parameters and results may be translated into real-world implications and vice versa. Details on this preparatory phase and its organizational setup are presented in Schmid et al. (2012b).

The focus of the research was on the one hand on the electricity sector - a sector for which technology options are readily available and where the discussion about mitigation has a longer lasting tradition in Germany. On the other hand, the transport sector was chosen as it is acknowledged that there are major difficulties in decarbonizing the transport sector (e.g. Luderer et al., 2012). Due to the limited scope of the project, a deliberation of technological mitigation options in the industrial and residential heat sector was not included in the participative process. However, the methodology outlined in Figure 1 and explained in the following can be transferred to more comprehensive scenario exercises in future research.

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. One dialogue was conducted for each sector to allow for an in-depth discussion. The interdisciplinary research team pre-selected focal topics for each sector by striking a balance between technological mitigation options that are crucial from the point of view of the energy-economy model and developments that are likely to be subject to controversies regarding their social acceptance. The NGO partners conducted the selection of participants so as to cover the range of interest groups as good as possible given the limited scope of the project. The 11 and 13 participants in the transport and electricity sector stakeholder dialogues included representatives from environmental NGOs, industry and consumer associations, topic-related interest groups, urban planning, trade unions and industry. A detailed list of the represented organizations can be found in the Appendix. During the stakeholder dialogues, pre-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 literature, the elicited data serves as a basis for generating sets of parsimonious narratives. Parsimonious narratives were developed for those mitigation options where stakeholders had an opinion and judgments on likely versus desirable developments diverged significantly or the desirability was particularly subject to dissent amongst stakeholders. This resulted in three scenarios. In order to keep the scenario definition tractable, a selection had to be made by the interdisciplinary research team and not all issues discussed during the stakeholder dialogues are actually differentiated in the scenarios. For those mitigation options which are not explicitly addressed by the scenario definition, the deployment decisions are endogenous to the model REMIND-D and boundary conditions are set equally for the scenarios according to expert judgments from literature. They can be consulted in the model documentation (Schmid et al., 2012a). It needs to be acknowledged that a mitigation scenario definition according to the criteria of likeliness, desirability with consent and desirability with dissent is not unique and influenced by the modeler's choice. Finally, the modeling team translates the parsimonious narratives 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. (2012a). 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. Mitigation is enforced by means of a strict emission budget of 16 Gt CO_2 over the time horizon of the analysis, 2005-2050, resulting in roughly 85% emission reduction in 2050 relative to 1990. The budget approach is inspired by Meinshausen et al. (2009). When budgeting emissions, the model can choose annual emissions endogenously allowing for flexibility 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, (iii) improving energy efficiency and (iv) reducing demand. The latter is generally avoided by the model as demand reductions have a negative impact on GDP. Limitations of REMIND-D are mainly that it abstracts from secondary and final energy imports and possesses coarse technology resolution in the residential and commercial heat sector. Further, infrastructure investments are only represented for energy distribution technologies but not for transport system infrastructure like railroad tracks due to a lack of data.

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 fossil primary energy carriers hard coal, natural gas and crude oil are imported at exogenous prices (Nitsch and Wenzl, 2009, price path B). Domestic lignite resources are represented by an extraction cost curve approach. Approximately 70 energy conversion technologies are considered explicitly, as are 20 distribution and 40 transport technologies. Conversion technologies produce the secondary energy carriers electricity, district heat, local heat, hydrogen, gas, petrol, diesel, kerosene and heating oil. Distribution technologies convert secondary energies into final energies as the industry and residential & commercial sector demands. Transport technologies provide energy services for passenger and freight relocation. Upon choice, the Carbon Capture and Sequestration (CCS) technology is available for the electrification and liquefaction of coal, lignite, gas and biomass from 2020 onwards. 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. Despite the time resolution in five-year steps, 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 as in the first round of dialogues 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 implications of technological mitigation options. 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 were defined according to the criteria of likeliness, desirability with consent and desirability with dissent. 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 favored e.g. by the coal industry. 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 with 11 participants. 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). It is intertwined through the indirect influence of transport technologies on production and distribution structures as well as other aspects of industrial organization and fundamental economic variables, e.g. the degree of specialization, economies of scale, comparative advantage and diffusion of technological progress. 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. However, 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. Biodiesel can be produced from bio-oils and bioethanol from sugar and starch biomass; in the future, second generation biofuels from lignocellulose will possibly become available (e.g. Schulz et al., 2007). Other low carbon technologies for fuel production include the liquefaction of hard coal or lignite in combination with CCS and a shift towards hydrogen. CSO stakeholders are controversial about the desirability of first-generation biofuels and doubt that second-generation biofuel technologies 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.

Table 2: Selected results of the Likert-Scale questionnaire of the CSO stakeholder dialogue on the electricity sector with 13 participants. 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

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. Yet CSO stakeholders expect electricity demand to remain stable or increase in the future, despite judging high efficiency growth rates as a desirable development. Institutional barriers to exploiting technical energy efficiency potentials are substantial, e.g. lack and asymmetry of information, principal-agent problems, split incentives, hidden costs or bounded rationality (Gillingham et al., 2004). Also, the rebound effect is likely to prove itself as a real obstacle. It postulates that energy efficiency increases make individual energy services cheaper, leading to an increase in their consumption or the consumption of other carbon-intensive energy services (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. 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). 33% of all energy-related German CO_2 emissions in 2009 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. As already mentioned, the deployment of all mitigation options not mentioned in Table 3 is left endogenous to the model REMIND-D. Given that all scenarios

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

are required to achieve ambitious mitigation, the scenario definition indicates that the 'continuation' scenario represents the most restrictive setup, especially because the freight transport and electricity sector are bound to certain CO_2 emissions by definition. Thus, the scenario constitutes a counterfactual exercise illustrating what would need to happen in the other sectors for achieving ambitious mitigation if these likely trends persisted and energy efficiency and REG potentials are not fully exploitable due to institutional barriers and societal resistance. On the contrary, the two 'paradigm shift' scenarios correspond to a world in which fundamental policy changes are successfully implemented. Here, tremendous progress is achieved in energy efficiency and REG deployment and carbon lock-in in terms of committed CO_2 emissions is avoided.

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. Before going through the results, it needs to be highlighted once more that they are derived under the assumption of perfect foresight and constitute deterministic first-best solutions rather than forecasts. This is especially relevant to the counterfactual 'continuation' scenario which is forced to achieve ambitious mitigation despite restrictive boundary conditions. Notwithstanding these abstractions, the scenario results yield valuable insights into stylized trends and interrelations across sectors under different scenario configurations. The following presents for each scenario the CO_2 emissions, trends in the transport and electricity sector as well as mitigation costs.

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. 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 originate in the prescribed increase in freight transport with trucks. 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 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' scenarios 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

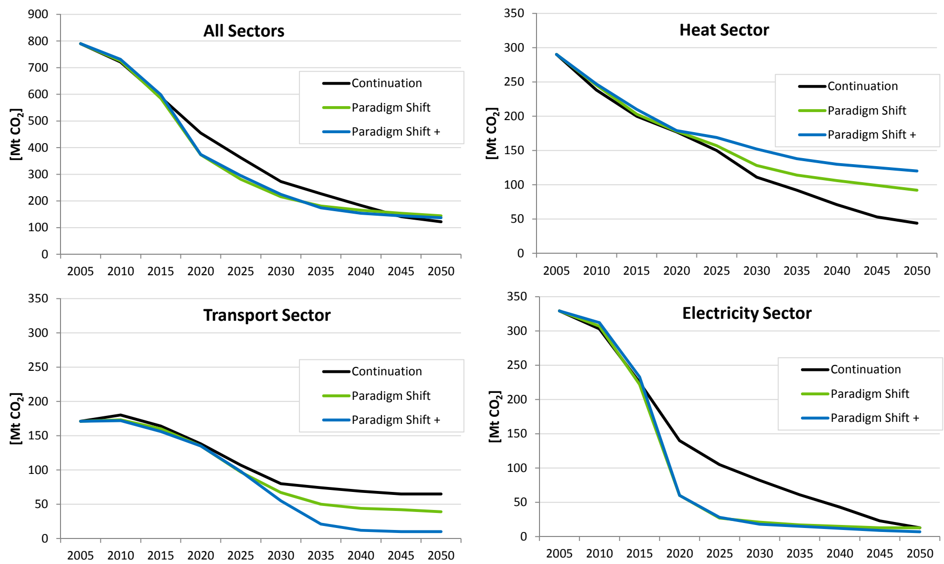

Figure 2: Annual CO_2 emissions from energy in Germany for 2005-2050 in Mt per year, by scenario and sector. These model results are obtained with REMIND-D

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 modeling 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.

Aggregate trends in the freight sector for each scenario are illustrated in Figure 3. The y-axis measures annual freight transport mileage in Bn t-km per year, whereas the x-axis displays the three sectors for each scenario. Time is indicated by color coding. First, Figure 3 visualizes the structure of the sectoral relationships in one scenario, highlighted by the connecting lines in the years 2005, 2020 and 2050. Second, the sectoral trends over time can be compared across scenarios. And third, it emphasizes the speed of transformation: The larger the white areas are within a bar, the faster is the CO_2 emission reduction between two time steps.

In all scenarios, freight transport by inland water navigation remains constant due to its limited potential. In the 'continuation' scenario, freight train capacities also remain at today's levels, however, freight transport with trucks increases continuously due to the scenario assumption of coupled GDP and freight transport growth rates. In 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.

As regards the passenger sector, annual per capita mileage 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.

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

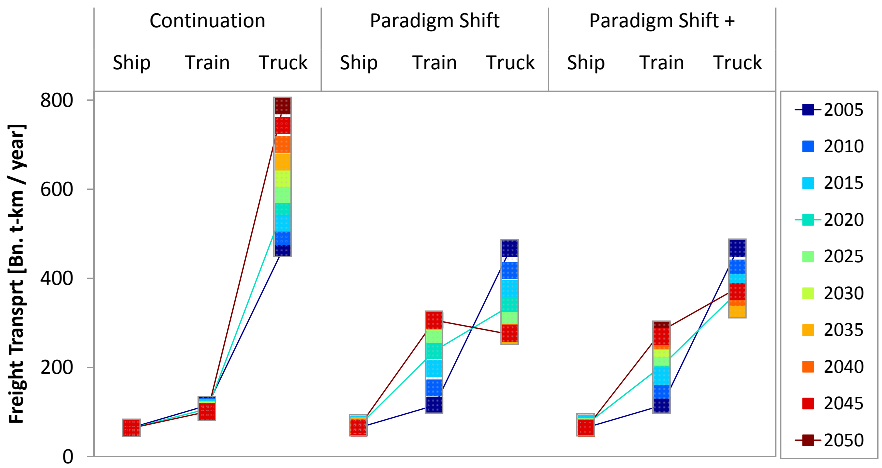

Figure 3: Annual freight transport mileage for 2005-2050 in Bn ton-km (t-km) per year, by scenario and mode. These model results are obtained with REMIND-D

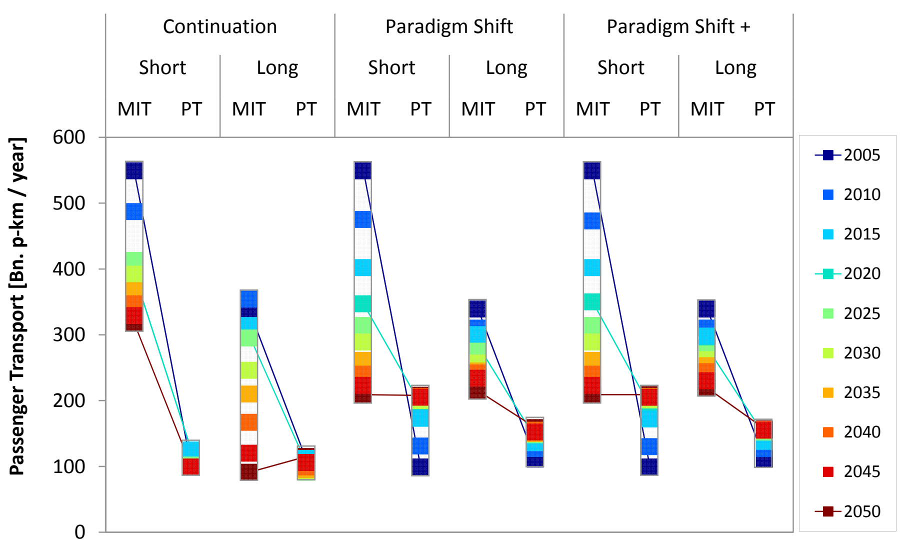

Figure 4: Annual passenger transport mileage for 2005-2050 in Bn passenger-km (p-km) per year, by scenario and mode. These model results are obtained with REMIND-D. MIT = Motorized Individual Transport, PT = Public Transport

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 the 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 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.

From 2020 onwards, the installed REG capacities stagnate in the 'continuation' scenario. This is due to the moderate potential in the scenario definition,

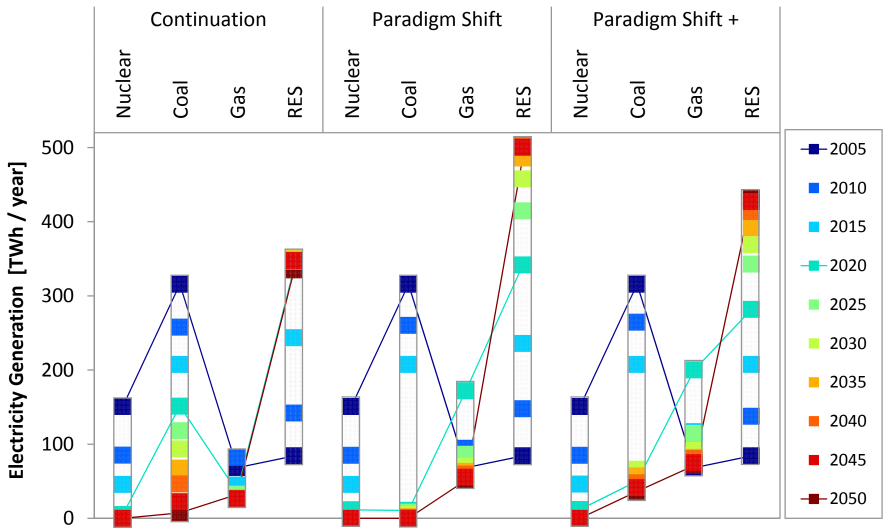

Figure 5: Annual electricity generation for 2005-2050 in MWh per year, by scenario and aggregated technologies. These model results are obtained with REMIND-D

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 TWh in 2005 to 375 TWh in 2050. 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 of 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.

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.

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. 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. 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). 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

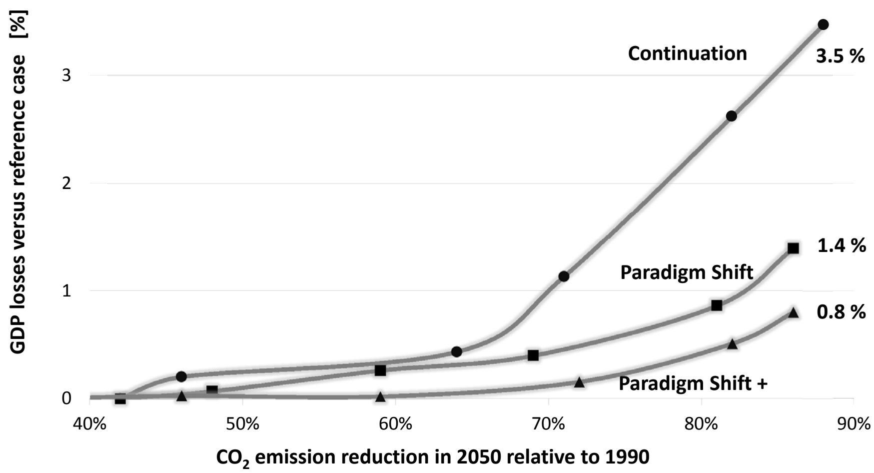

Figure 6: Mitigation cost curve for the three scenarios, in terms of cumulative discounted GDP losses compared to a respective reference scenario with 40-45% CO_2 emission reduction in 2050. These model results are obtained with REMIND-D.

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 because of 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 and in line with findings in other scenario exercises (e.g. Edenhofer et al., 2010; Luderer et al., 2012). 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 mainly due to socio-political implications that conflict with objectives in 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 substantially. 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 implications 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 likely be out of reach.

The 'paradigm shift' scenarios see the carbon lock-in resolved. CSO stakeholders largely corroborate the desirability of its proposed developments, especially the fast increase in renewable electricity generation. However, they point out that several model projections appear unrealistic such as the near-term decommissioning of coal power plants, the rapid shift from road to rail in freight transport or the widespread electrification of private transport until 2030 and the simultaneous shift to public transport. They doubt that it is possible to establish the necessary collective political will for enforcing policies that lead to such technology deployment.

Several concerns were articulated 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, the projected rapid decommissioning of existing coal power plants may entail increasing regional unemployment rates in Germany's structurally weak lignite mining areas. Finally, a fast deployment of renewable electricity generation and transmission line capacities requires high procedural justice throughout the planning and installation process, including institutionalized possibilities for local communities to participate, also financially. CSO stakeholders preferred 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.

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. During separate dialogues, their preferences on future developments related to mitigation in the transport and electricity sector were discussed and elicited. Along with findings from literature, the input from the CSO stakeholders built the basis to generate parsimonious narratives on future developments of key variables in the transport and electricity sector according to the criteria of likeliness, desirability with consent and desirability with dissent.

The 'continuation' scenario is characterized by enforcing 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. 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 CO_2 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. Stakeholders judged the results of this counterfactual scenario as highly problematic from a socio-political point of view and conclude that under carbon lock-in, ambitious mitigation will likely be out of reach.

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 widespread electrification of private transport by 2030, 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. Yet the necessary fundamental policy changes for such a scenario are put into question by stakeholders as they doubt that sufficient collective political will can be established. The 'paradigm shift+' scenario which additionally allows for the controverial 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, particularly due to social refusal.

Overall, the deliberative elements in this participatory mitigation scenario exercise have demonstrated that the transformation towards a low-carbon energy system constitute as much a societal effort as an engineer's project. Socio-political implications of technological mitigation options are abundant and would indeed have an impact on the society as a whole. It is questionable, however, if the institutional aspects to the use of energy services can be adapted as rapidly as suggested by the optimal scenarios derived under the assumption of perfect foresight. This corroborates the thoughts of Unruh (2000) who suggests that energy model results are biased due to abstracting from technological evolution and institutions. He argues that sectors of the energy systems cannot be comprehended as discrete technological artifacts but rather as complex systems of technologies embedded in a powerful conditioning social context of public and private institutions.

However, the direct implementation of social context and institutions into numerical energy system models appears impossible due to a lack of theoretical concepts and unobservability of data. In order to attach contextual meaning to parameters in available energy system models, the use of narratives, as explored in this paper, proves to be a promising avenue. Pursuing a participatory approach to developing mitigation scenarios results in a much stronger focus on the process of scenario definition and evaluation and allows for the explicit attachment of normative consideration to modeling results. As a form of scientific policy advice, such scenarios deal with value judgments openly and do not attempt to hide them behind seemingly factual or technical statements.

Even though the limited scope of this research impedes inferential conclusions on the German energy transition as a whole, it has demonstrated that the technological solutions to the mitigation problem proposed by the model results give rise to significant societal and political implications that deem at least as challenging as the mere engineering aspects of innovative technologies. These insights underline the importance of comprehending mitigation of energy-related CO_2 emissions as a socio-technical transition embedded in a political context. Thus, in future mitigation scenario exercises the questions of how to govern the transition and which kinds of policy instruments are suitable for enabling the transition should be treated more explicitly. If this participatory research could be repeated under these considerations and at larger scope and scale, emerging mitigation scenarios potentially enjoyed a higher level of ownership and acceptance amongst societal and political actors and ideally contributed to shared vision-building.

Acknowledgements

This research was partly funded by the project ENCI-LowCarb (213106) within the 7th Framework Programme for Research of the European Commission. The authors would like to thank the ENCI-LowCarb partners, especially Jan Burck (Germanwatch) for the inspiring teamwork as well as Michael Pahle and two anonymous reviewers for insightful comments.

Appendix

List of organizations participating in the stakeholder dialogues on the transport sector: World Wide Fund For Nature (WWF), Germanwatch e.V., FUSS e.V. - Fachverband Fußverkehr Deutschland, Verkehrsclub Deutschland e.V, Allgemeiner Deutscher Automobil-Club e.V. (ADAC), Allgemeiner Deutscher Fahrrad-Club e.V. (ADFC), Verband Deutscher Verkehrsunternehmen e.V. (VDV), Allianz pro Schiene e.V., Region Hannover Verkehrsentwicklung und Verkehrsmanagement, Daimler AG, Verband der deutschen Biokrafstoffindustrie e.V.

List of organizations participating in the stakeholder dialogues on the electricity sector: Naturschutzbund Deutschland e.V. (NABU), klima-allianz deutschland, e5 - European Business Council for Sustainable Energy, World Wide Fund For Nature (WWF), Germanwatch e.V., Brot für die Welt (Diakonisches Werk der Evangelischen Kirche in Deutschland e.V.), Bundesverband Erneuerbare Energie e.V. (BEE), Bundesverband Verbraucherzentralen, TenneT TSO GmbH, 50Hz Transmission GmbH, LichtBlick AG, RWE AG, Industriegewerkschaft Bergbau, Chemie, Energie (IG BCE).

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