EXPLORING THE FEASIBILITY FRONTIER FOR AMBITIOUS CLIMATE MITIGATION TARGETS IN GERMANY

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1 Introduction

Toward which domestic CO_2 mitigation target should Germany aim in the long-run? This question is central for national policymakers who bear in mind the success of global efforts to avoid dangerous impacts of anthropogenic climate change. Albeit political efforts have been increasingly visible during the past decade, industrialized countries had difficulties with achieving substantial progress in reducing CO_2 emissions: Germany has managed to advance from a 15% reduction in 2000 vs. the 1990 level to 20% in 2008 (UBA, 2009). Yet, the political and societal awareness for decarbonization is relatively high as compared to other countries and government targets for mitigation are quite ambitious: In its "Energy Concept" the German government has formulated target CO_2 emission reductions versus the 1990 level of 40% in 2020, 55% in 2030, 70% in 2040 and 80-95% in 2050 (BMWi & BMU, 2010). The question is whether these targets are achievable, both from a technological and economic point of view.

To give a definite answer is certainly challenging as it will strongly depend on a variety of expectations about technological and structural developments over the next four decades, e.g. the availability of the carbon capture and sequestration (CCS) technology or extending electricity grids. These developments are in turn the outcome of societal choices involving many stakeholders and as such represent framing conditions that define the scope of technical mitigation options. For an assessment of the window of opportunity for domestic mitigation in Germany it appears hence unavoidable to think about the future in scenarios. When analyzing a scenario, one simplifies the complexity of the problem by assuming that certain societal choices have been made and then focuses on their specific implications. In this spirit, several valuable publications (e.g. BMU, 2009; WWF, 2009; UBA, 2010; SRU, 2010; BMWi, 2010) have analyzed ambitious domestic mitigation scenarios with different energy system models and find that they are technically feasible, given the respective assumptions. As they predominantly employ bottom-up simulation methods focusing on details within one scenario, the capacity for comparing a large number of scenarios with differing framing conditions is limited. Further, simulation methods do not ensure optimal mitigation pathways in the sense that they discovered where, when and how mitigation should take place so decarbonization is achieved at lowest possible economic costs. With the aim to complement the existing research, this paper analyzes how assumptions on framing conditions impact the relationship between economic costs and the level of ambition for domestic CO_2 mitigation targets. The corresponding intertemporally optimal decarbonization pathways are calculated by means of a comprehensive scenario analysis with the

hybrid energy system and macroeconomic model REMIND-D. From a modeling point of view, the results indicate that assumptions on the development of framing conditions for mitigation options are indeed essential for assessing the economic and technical feasibility of ambitious CO_2 emission reduction targets.

The structure of the paper is as follows: Section 2 elaborates the methodology by introducing the model REMIND-D and relevant framing conditions as well as the concept of mitigation costs curves in conjunction with economic and corresponding technical feasibility frontiers. Section 3 presents mitigation cost curves, CO_2 prices and emission reduction pathways for each scenario. Section 4 provides a discussion and wraps up with emerging implications for the future of the German energy system.

2 Methodology

The model REMIND-D that is used for the analysis is a coupled energy system and macro economy model of Germany. The outstanding features of REMIND-D, as compared to other energy system models of Germany, are that the majority of structural relationships are endogenous and non-linear features such as learning-by-doing are incorporated. As such, the model setup allows for a large number of sensitivity studies. For more detailed information about the model see the extensive model description in Schmid et al.(2011), also provided online[1]. In the next subsection the most important aspects about the model REMIND-D are presented, followed by a discussion of six mitigation options that may be exploited for managing ambitious mitigation targets and an explanation of how they are implemented into the model. Finally, Section 2.3 provides a conceptual discussion of how the impacts of different configurations of framing conditions can be measured by analyzing the set of mitigation cost curves emerging in the different scenarios. We propose to employ corresponding economic and technological feasibility frontiers for assessing the window of opportunity for ambitious domestic mitigation pathways in Germany. The assessment can go in both directions in the sense that, given the different assumptions about the development of framing conditions for mitigation options, one can evaluate the corresponding range of economic costs for a certain mitigation target or, vice versa, the range of achievable mitigation targets for a selected tolerable level of economic costs.

Available online at http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/groups/esm-group/remind-d-model-description

2.1   The model REMIND-D

REMIND-D (Refined Model of Investment and Technological Development - Deutschland) is a general equilibrium model that uses intertemporal optimization methods for solving the equilibrium problem. The time horizon under investigation is until 2050 and the resolution is a five-year step. It combines all the features of a detailed bottom-up energy system model with those of a top-down macroeconomic production function. Hence, supply and demand side can be analyzed hand in hand. REMIND-D is calibrated for the year 2007 regarding the demand of different final energy carriers of the two aggregated sectors industry and residential/commercial as well as different energy services (expressed in person- or ton-km) in the transport sector[2]. Historical data incorporated include detailed information about existing generation capacities[3] and their expected technical lifetimes. New generation capacities can be built in every time step, however, excessive capacity increases within one time step are prevented by punishing this behavior with adjustment costs that are determined endogenously and serve to represent the observation that excessive capacity increases in reality incur additional costs due to bottlenecks.

The energy system module is provided with a rich parameterization of established and innovative energy conversion technologies. Conversion technologies transform exhaustible and renewable primary energies into secondary and final energy carriers as well as energy services[4]. Over time, the different energy demands develop endogenously by means of a nested constant elasticity of substitution (CES) production function considering capital, labor and energy with the latter split into different subnests for the three sectors mentioned. The Gross Domestic Product (GDP) generated by the production function in a respective time step needs to cover the investments into the macroeconomic capital stock as well as all energy system expenditures (capital investments, operation and maintenance costs and fuel costs). The remainder is considered as money disposable for consumption entering the optimization objective. An intertemporally optimal allocation of investment streams into the conversion technology's capacities and the macroeconomic capital stock is ensured by the solving algorithm.

For the analysis at hand mitigation is enforced by imposing a constraint on the budget of CO_2 emissions allowed over the optimization period, inspired by Meinshausen et al. (2009). The

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[2] The data is taken from the German energy balances (AG Energiebilanzen, 2009) and transport statistics (Verkehr in Zahlen, 2008). For detailed information please consult the model description.
[3] These are from UBA (2008) and are in aggregate capacities per technology.
[4] A complete description of all conversion technologies and their techno-economic parameterization is provided in the model description.

advantage of a CO_2 budget as opposed to prescribing an emission path is that the solving algorithm determines the optimal pathway of emissions endogenously. The model is run in a cost-effectiveness mode, meaning that climate-policy objectives are considered, but not damages from climate change impacts. Mitigation options in the energy system include the use of technologies that rely on renewable energy sources or biomass and the use of carbon capture and sequestration (CCS) in combination with hard coal, lignite, gas or biomass. Additionally, in the macroeconomic module mitigation can be achieved by substituting carbon intensive input factors for less carbon intensive input factors or demand reduction, which is to be interpreted as improving energy efficiency. The effects of imposing more ambitious mitigation objectives within the model can be analyzed by comparing the results from a model run with a relatively larger emission budget, serving as a benchmark, with those of a model run with a stricter budget. All other parameters and assumptions are equal for assessing the effect of stricter emission budgets. As we consider various scenarios in this analysis that differ in their assumptions on several issues there is be a benchmark case for each scenario, relative to which mitigation costs are determined.

The measure of economic costs for mitigation considered in this analysis is the sum of discounted[5] yearly GDP differences between a pair of benchmark and ambitious mitigation model runs over the time span 2010-2050. As the topic of interest is the economic and technical feasibility of *ambitious* climate mitigation targets, the corresponding benchmark of each scenario is defined as exhibiting moderate mitigation commitment and achieves around 40 % CO_2 emission reduction in 2050 versus the 1990 level[6]. This corresponds to a five percentage point improvement in each coming decade and is basically an extrapolation of the improvement rate of the last decade. Note that within this framework, imposing stricter CO_2 emission budgets will generally lead to economic costs as compared to the respective benchmark since the introduction of an additional constraint restricts the optimization and potential positive effects of mitigation, e.g. labor market effects or in general a cleaner environment and less air pollution, are beyond the scope of the model. To summarize, the economic mitigation costs reported in the results part are to be interpreted as cost differentials for ambitious targets as compared to moderate targets.

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[5] The discount rate used is 3%, which corresponds to the internal discount rate in REMIND-D.
[6] The reason why the baseline of each scenario achieves a slightly different target in 2050 is that the framing conditions differ across scenarios for the policy as well as the baseline case. The range is 36-40% CO_2 emission reduction versus the 1990 level in 2050.

2.2   Framing Conditions and Scenario Setup

As introduced before, the term framing conditions in this paper expresses outcomes of societal choices that in their sum determine the window of opportunity for ambitious domestic CO_2 emission reduction pathways. Pursuing ambitious mitigation options certainly implies structural breaks in technological development paths in the form of large-scale deployment of efficient low-emission technologies. Decisions of when to opt for what technological option in which sector are strategically complex and involve a very large and diverse group of stakeholders. However, some configurations of framing conditions enable mitigation pathways that are achievable at economically lower costs than others. The triangular tradeoff between tolerating economic costs, managing ambitious emission reduction targets and taking care of selective stakeholders' interests is nontrivial to resolve. We identified six mitigation options that may be exploited for managing ambitious CO_2 emission reuction targets in Germany, the realization of which, however, depend on the development of framing conditions. The issues are: (i) Whether the option to make use of the Carbon Capture and Sequestration (CCS) technology is viable, (ii) the domestic renewable electricity potential may fully be accessed, (iii) decommissioning existing coal power plants is an option, (iv) strong efficiency growth rates are achievable, (v) biomass shall be harvested for energy purposes or (vi) a reduction of freight transport with trucks is possible. The realization of each mitigation option is, as the name suggest, optional and principally subject to societal choice and the availability of the technological options for large-scale deployment. Table 1 illustrates the bottlenecks, prerequisites and problems associated with each of the six mitigation options and assigns specific keywords for shortage of notation.

For an analysis of the impacts of activation each mitigation option, a reference scenario is defined, in which none of the options are available. This is to be interpreted as a future in which one expects structural developments to happen without major efforts to make the "extra" mitigation options accessible. It will be referred to as the REFERENCE scenario hereafter. To assess the impact of accessing each mitigation option, six scenarios are defined which are similar to the REFERENCE scenario with the exception of the one option of interest. These will be referred to with the associated keywords. Further, one could imagine scenarios in which the joint availability of mitigation options creates synergies. Several such configurations will become evident throughout a discussion of the implementation of the mitigation options into the model REMIND-D.

Mitigation option	Bottlenecks / Prerequisites / Problems	Keyword
Carbon Capture and Sequestration (CCS)	Availability, pipelines, storage sites, legal issues, social acceptance	CCS
Large domestic renewable electricity potential	Domestic Grid and/or Interconnector extension, storage, social acceptance	RES+
Not use conventional coal power plants any more	Enough renewable electricity generation, CCS retrofit, devaluation of financial assets	COALOFF
Very high efficiency growth rates	Rebound effect, habit	EFF+
Large domestic biomass potential	Food competition, environmental issues	BIO+
Decoupling truck freight transport and GDP	Freight rail capacity	RAIL+

Table 1. Overview of the six mitigation options considered in this analysis, the realization of which is determined by the development of framing conditions, with associated conceptual bottlenecks, prerequisites. problems and the respective keywords.

The availability of the mitigation option of employing the CCS technology in combination with hard coal, lignite or biomass transformation technologies is to date not clear for Germany. For having the CCS technology as a mitigation option in by 2020, one had to invest in sequestration sites and pipeline infrastructure in the very near-term future. Yet, a coherent legal framework does not exist to date and the social acceptance in those communities near explored storage sites is very low. As regards the implementation, in the REFERENCE scenario the technology is principally not available for the model. In the CCS policy scenario, it is assumed to be an option from the year 2020 onwards and the overall storage potential limited to 10 Gt CO_2. This is a relatively moderate estimate from Knopf (2010) as the range goes up to 40 Gt CO_2, however, these estimates are relatively vague.

Estimates for the technical potential for each renewable energy source in the existing literature vary substantially as illustrated in Table 2. The maximum potentials assumed for the REFERENCE and the RES+ policy scenario are in the outer right columns with the latter representing the highest estimates considered in the literature. Bottlenecks for exploiting these potentials are, however, the speed of electricity grid extension, which is slowed by regulatory and legal uncertainties, and the construction of Interconnectors and/or storage facilities to overcome the technically problematic issue of making demand match fluctuating supply. Especially the construction of grids crossing service area boundaries has been proven to be very slow in the past years due to a lack of social acceptance for the necessary infrastructure projects.

TWh/a	Nitsch (2004)	BMU (2008a)	UBA (2010)	DLR (2010)	REMIND-D REFERENCE	REMIND-D RES+
Solar-PV	105	105	248	112	105	248
Wind-Onshore	60	68	180	90	90	180
Wind-Offshore	85	135	180	317	180	317

Table 2. Overview of technical potential estimates in TWh/a for renewable energy sources of different potential studies for Germany. The REMIND-D potentials are further based judgments by UBA experts and Paschen et al. (2003).

Another option for reducing CO_2 emissions in the electricity sector is not to continue using existing conventional hard coal or lignite power plants, even if they did not reach the end of their technical lifetime yet. This may either be an optimal choice if renewable energy production increased substantially and load management became difficult or if the plants may be retrofitted with CCS applications. In the case of the former development, from a business point of view the option classified as a devaluation of financial assets, which is certainly not in the interest of the affected stakeholders. The operationalization in the model in the COALOFF scenarios is implemented in the form of an option not to use existing coal power plants without incurring costs. Yet, if an existing capacity has not been used in a certain year, may not be put in place again for the rest of the optimization period. One can expect that this option enhances the economic feasibility of ambitious mitigation only in combination with either the RES+ or the CCS option allowing for a low-emission replacement of the generation capacities.

Efficiency growth rates of the final energy demand of the residential and commercial sector and the industry sector have been about 0.5 % annually in the past two decades in Germany (AG Energiebilanzen, 2009 and own calculations). For the REFERENCE scenario we assume a moderate average increase of the efficiency growth rates of 1.3% per year. In the EFF+ scenario we assume that the general awareness for energy efficiency improvements is very high and the growth rate of efficiency improvements amounts to 2.3% per year. Pursuing this mitigation option is very ambitious as it required collective action with ideally the participation of all individuals, families, firms, communities and the government. Furthermore, a great deal of energy efficiency improvements has to do with personal habit, which will only change upon conscious choice. The occurrence of significant rebound effects is another obstacle for this mitigation option. Rebound effects describe the empirical evidence that once energy efficiency is improved for some applications there is a tendency to consume more and thereby eliminate the savings.

Biomass is a very flexible primary energy resource that may be used in combination with a large variety of conversion technologies transforming biomass into electricity, gas, heat or fuels. Regarding the emission CO_2, the cultivation of biomass is relatively emission neutral. However, indirect emissions from land use change also contribute to the greenhouse gas effect. Domestic biomass potentials are constrained by the competition with food production and environmental considerations. Table 3 presents the technical potentials assumed in the REFERENCE and BIO+ scenarios, which are identified in the literature. Increasing the amount of harvested domestic biomass is an interesting option especially when CCS is available as this combination has the potential to extract CO_2 from the atmosphere and thereby create negative emissions.

| Potential [PJ/a]	Bio/LC (Lignocelluloses)	Bio/S&S (Sugar / Starch)	Bio/Oil (Oil)
REFERENCE	450/700	40/250	40/200
BIO+	450/1200	40/400	40/300

Table 3. Biomass potentials in REMIND-D. The first value corresponds to the potential in 2005, which linearly increases to the second value - the potential in 2050. The REFERENCE Scenario values are from Nitsch et al. (2004) p. 160-161, variant „Naturschutz Plus", Scenario B; here it is assumed that only residue and waste material enter the lignocelluloses potential. The agricultural land which may be used for growing sugar/starch and oily biomass may increase at the most by factor four compared to 2005. The BIO+ Scenario value for lignocelluloses is from Aretz and Hirschl (2007) and for the production of energy crops it is assumed that an extensive increase in farmland is pursued. Potential estimates for the latter are from the Nitsch et al. (2004) Reference Scenario and DBFZ/ OEKO (2009). Potentials are in terms of lower heating values.

As there is empirical evidence on the direct relationship between the GDP growth rate and the growth rate of freight transportation with trucks, we prescribe REMIND-D in the standard configuration to increase the ton-km driven each year as forecasted in the Shell Truck Study (2010). The reason is that in the model setup of REMIND-D, there is no explicit causal link between GDP growth and freight transport with trucks. In the RAIL+ scenario we leave the decision on the development of the freight sector endogenous and the model always chooses to significantly increase freight train mileage and significantly decrease truck mileage. However, this development is not foreseeable in the near-term future and implies large investments upfront into the rail track infrastructure which is not likely to happen without a major paradigm change.

The discussion illustrates that the exploitation of each option has its own merits, drawbacks, bottlenecks and a long lead-time for realization in most cases. The next section establishes a framework for understanding the impacts of the presented mitigation options on economic costs.

2.3   Mitigation cost functions and feasibility frontiers

As introduced in Section 2.1, mitigation costs are here defined as the sum of discounted GDP differences between a pair of benchmark and stricter emission budget model runs until 2050. With REMIND-D, we calculate the mitigation costs for each framing condition scenario with several CO_2 emission budgets variants. They result in abatement levels for the year 2005 in the range from 70% to very ambitious 80-95% as compared to 1990 levels, depending on the specific assumptions on framing conditions for the scenarios. If we plot the economic mitigation costs against the level of domestic CO_2 emission reduction achieved in 2050 for each scenario, we obtain a mitigation cost curve for the whole of the German energy system.[7].

CO2 emission reduction in 2050 relative to 1990 levels
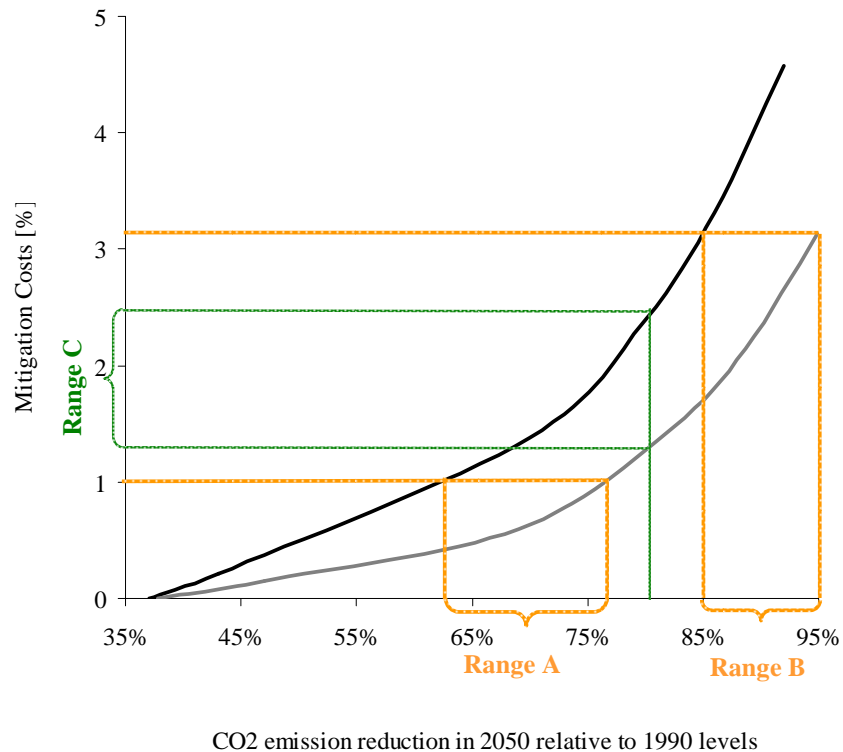
Figure 1. Conceptual illustration of mitigation cost curves o the   German energy system for two representative scenarios differing in the definition of framing conditions and illustrative economic and technological feasibility frontiers. The grey curve represents a scenario with a relatively richer set of mitigation options. Horizontal lines are economic feasibility frontiers; vertical lines are technological feasibility frontiers. Once the desired economic feasibility frontier is fixed at a certain level, e.g. 1% or 3%, the corresponding technological feasibility frontiers, located at the intersections with the mitigation cost curve span the windows of opportunity for achieving mitigation targets, here ranges A and B. Upon fixing the desired technological feasibility frontier, e.g. at 80%, the corresponding economic feasibility frontiers span the window of opportunity in terms of mitigation costs, range C.

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[7] Due to numerical complexity we calculate five emission budget variants for each framing condition scenario and then interpolate the cost curve, differences between the interpolation and more refined intermediary results turn out to be negligible.

Figure 1 provides a conceptual illustration of how to interpret the mitigation cost curves of scenarios differing in their framework conditions by means of economic (horizontal lines) and technological feasibility frontiers (vertical lines) that span the associated economic or technological windows of opportunity. The framework proposed allows for a visual overview of the impacts of qualitatively different structural developments on mitigation costs and mitigation targets. It needs to be emphasized that the normative evaluation of what is a tolerable economic cost level and what is a desirable mitigation target is up to the German society. Here we want to sketch the windows of opportunity emerging from possible future developments. In the conceptual presentation, the grey mitigation cost curve represents a scenario with framing conditions that enable a richer set of technological mitigation options than in the black case. The slope of the grey mitigation cost curve is increasing at a slower rate than that of the black one, indicating that due to the richer set of mitigation options, ambitious abatement targets can be achieved at relatively lower economic costs. Mitigation cost curves may be interpreted both from the economic as well as the technological point of view as suggested by the arrangement of the associated orange and green feasibility frontiers.

From an economic point of view, the horizontal orange bottom line indicates the normative choice that mitigation costs of 1% GDP losses over the period 2010-2050 were a tolerable level. If those framing conditions represented by the black mitigation cost curve were realized, a 62% CO_2 emission reduction target could be met by 2050. If, however, the framing conditions developed as assumed for the grey mitigation cost curve, a 77% emission reduction target could be achieved at the same economic cost. Assuming the society considered 3% GDP losses as a tolerable level as indicated by the upper orange economic feasibility frontier, the window of opportunity for mitigation targets ranged from 85% to 95%. As an example for evaluating from the technological point of view, the vertical green line represents a desired mitigation target of 80% - the corresponding green economic feasibility frontiers indicate that given the grey framing conditions GDP losses of 1.2% would be incurred. In the black scenario with the GDP losses were twice as high with 2.5%. This illustrates that if societal choices on mitigation options were such that they allowed for a realization of those options, more ambitious CO_2 mitigation targets could be met at lower economic costs. Finally, the next section presents the mitigation cost curves emerging for a selection of scenarios that represent possible structural developments of the German energy system.. We refrain from drawing feasibility frontiers in the graphs but encourage the reader to read the graphs in a similar way than just outlined.

3   Results

After the scenario definitions and the conceptual idea have been established, we now turn to presenting the mitigation cost curves, first for scenarios with single variations of framing conditions and then for selected scenarios with joint variations. Graph 1 displays the mitigation cost curves of the German energy system for the single variation scenarios.
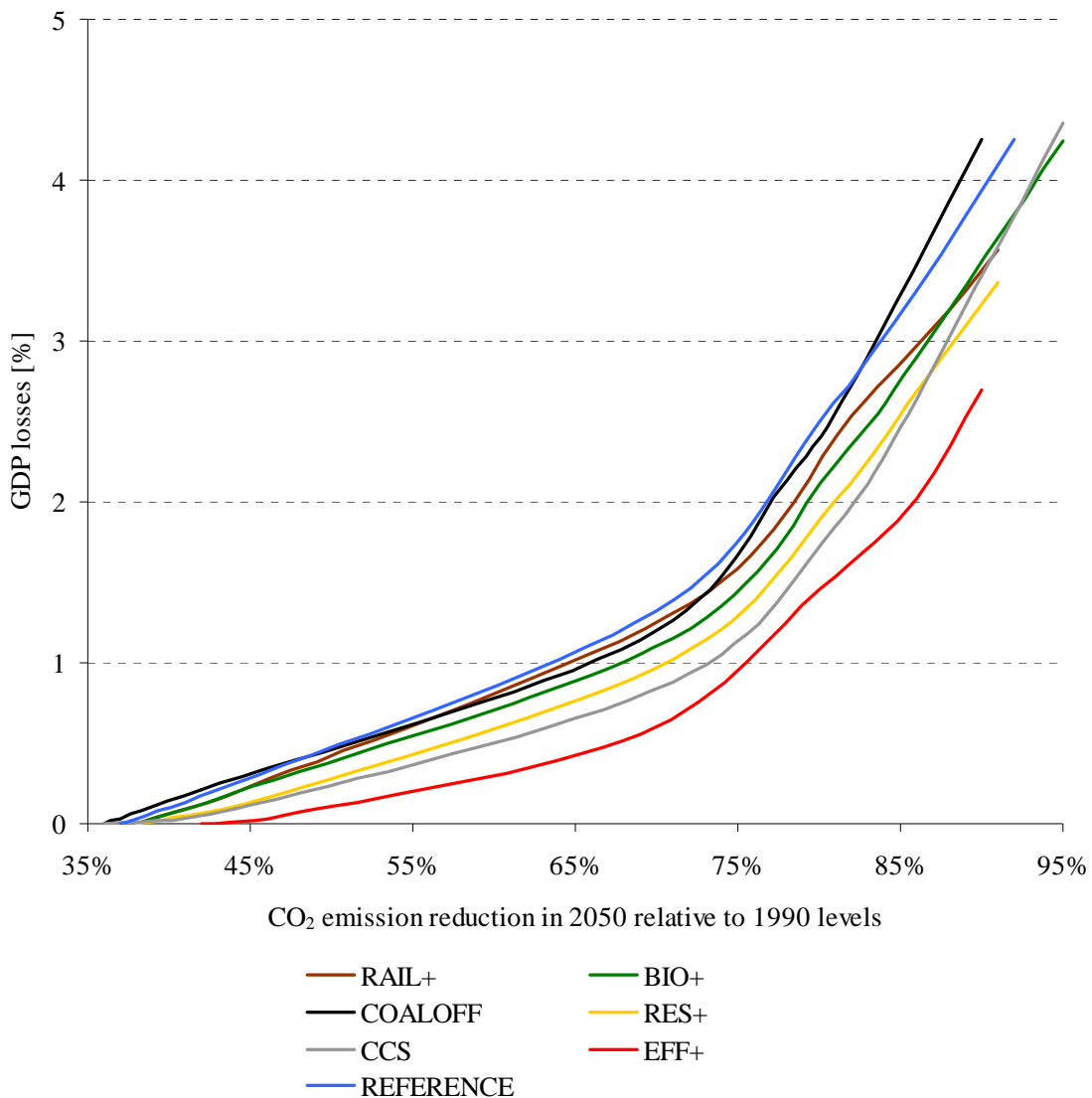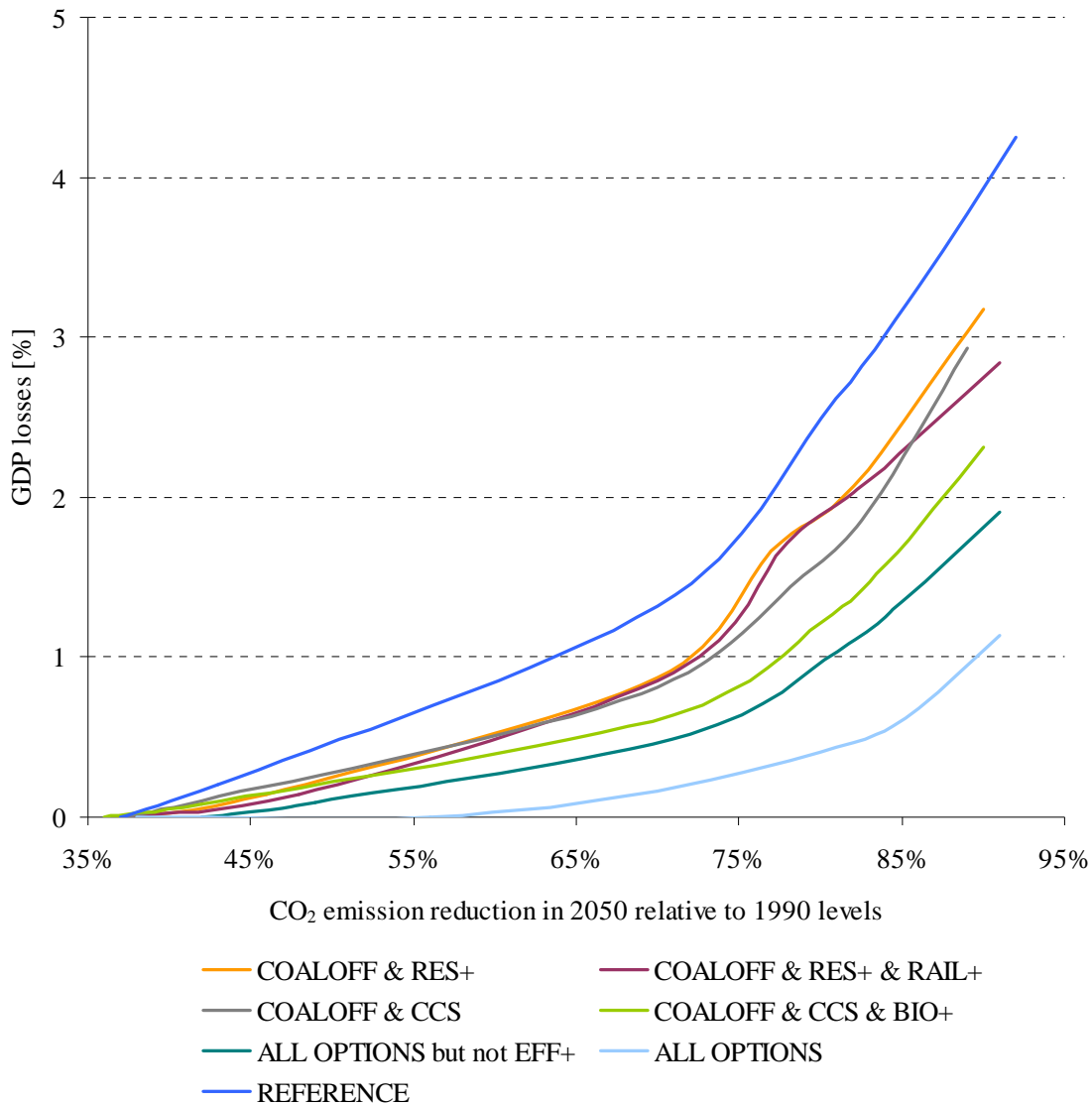

Graph 1. Mitigation cost curves of the German energy system for the six framing condition scenarios defined in Section 2.2. They are similar to the reference scenario with the exception of the one option of interest, which is represented by the respective keyword. The horizontal axis shows the CO_2 emission reduction target achieved in 2050 versus the 1990 level. The vertical axis indicates the GDP losses over the period 2010-2050 in percentage-points as compared to the corresponding baseline scenario.

One feature that becomes evident from a first glimpse on Graph 2 is that the various mitigation cost curves do have different start and end points. For one, they do not intersect the horizontal axis at the same mitigation target. This is owed to the practice of implementing the mitigation constraint into the model by means of a CO_2 emission budget over the optimization time horizon. The solving algorithm then determines an intertemporal optimal emissions path. As the defined "extra" technological mitigation options assumed in each scenario are also available in the baseline case the mitigation targets achieved in the respective baselines differ. This is because the various "extra" mitigation options have an impact on shape of the intertemporally optimal emission path. At a close look, especially the EFF+ mitigation cost curve achieves a higher emission target in the baseline illustrating the powerful effect of energy efficiency improvements. Before turning to the interpretation of the differences between the mitigation cost curves, notice the different end points in terms of achievable mitigation targets. The curves end for the tightest possible emission budget that yields a feasible solution from the solving algorithm. As the question of what was the highest achievable mitigation target for each scenario is not in the focus of this analysis, we do not want to stress the horizontal differences between the very end points so much. Of particular interest, however, is the shape of the mitigation cost curves in the range of 70% to 90% CO_2 emission reduction targets.

The tighter the emission budget, the more mitigation options need to be exploited from the model's point of view. As low-emission technologies are to date more costly than those relying on fossil resources, major investment streams are necessary for building up capacities and exploiting cost reductions via learning curve effects. The framing conditions in each scenario define the availability of mitigation options that differ in their cost-structure and technical characteristics. Consequently, we expect that mitigation cost curves of scenarios with framing conditions that enable advantageous options exhibit a flatter slope. Options may be classified as advantageous because either they are more cost-efficient than substitutable technologies, or they supply a particularly demanded kind of final energy or energy service at low emissions, or they access a resource that may otherwise not be accessed. The latter is the case in the BIO+ and RES+ scenarios since they are defined by higher resource potentials. As compared to the REFERENCE scenario, the mitigation cost curves shift to the right and become somewhat flatter towards more ambitious emission reduction. As such they enable slightly higher mitigation targets at the same economic cost levels. In case of the RAIL+ scenario, the possibility to significantly reduce CO_2 emissions in the freight transport sector by means of rail transport represents the case where a demanded energy service can be supplied at lower emissions. Here

the mitigation cost curve flattens significantly from 80% CO_2 emission reduction targets upwards indicating that this option is especially valuable when aiming at really ambitious mitigation targets. To continue, the option to not use conventional coal power plants anymore by itself is only beneficial for mitigation targets of up to 70%. Here the oldest power plants with low efficiency factors are replaced with more efficient generation capacities. If, however, the mitigation target is really ambitious, all existing coal power plants are shut down by 2020 and the necessary fast build-up of replacement capacities incurs adjustment costs that are higher in the COALOFF than in the REFERENCE scenario. For this reason the mitigation cost curves cross each other. Graphh 1 confirms the expectation that the COALOFF option is not necessary useful as a singular option. Further, the opportunity to use the CCS technology allows for exploiting fossil resources at very low CO_2 emissions or even create negative emissions in combination with biomass. For mitigation targets up to roughly 85%, the CCS scenario implies slightly lower economic feasibility frontiers than those of the RES+ scenario. The option of a substantial increase in efficiency improvements is even more potent in terms of widening the window of opportunity at given economic cost levels. Now, the important point to investigate is if there occur significant synergies upon combining certain mitigation options and of course also how wide the window of opportunity for domestic emission reduction spans once all mitigation options are activated.

Graph 2 illustrates the mitigation cost curve for several combinations of jointly altering the framing conditions. As already addressed, the combination of COALOFF and RES+ or COALOFF and CCS creates synergies as becomes evident when looking at the orange and grey mitigation cost curves of the two scenarios. In the COALOFF & CCS scenario, the reduction in GDP losses as compared to the REFERENCE case for a given mitigation target is slightly higher in the joint scenarios than the sum of the cost differences between the single scenarios and the REERENCE case. The mitigation cost curve of the COALOFF & RES+ scenario exhibits a kink in emission target range between 70% and 80%. Adjustment costs are once again the reason here. For emission budgets stricter than yielding 70% reduction, the immediate pullout of conventional coal power plants makes strong investments into renewable energies necessary. Such a fast built-up of capacities comes more expensive than a smooth one. Yet, the option of a decentralized renewable electricity sector demands the same GDP losses for a 90% reduction target than the one of a more centralized electricity sector employing CCS. We need to emphasise, however, that even in the COALOFF & CCS scenario a large share of renewable electricity production is occurring.

Graph 2. Mitigation cost curves of the German energy system for joint combinations of the various framing condition scenarios defined in Section 2.2. They are similar to the reference scenario with the exception of the options of interest, which are represented by the respective keywords. The horizontal axis shows the CO_2 emission reduction target achieved in 2050 versus the 1990 level. The vertical axis indicates the GDP losses over the period 2010-2050 in percentage-points as compared to the corresponding baseline scenario.

The purple curve adds the option increasing rail freight traffic and one can notice very impressively how this flattens the mitigation cost curve for very ambitious targets. It is a matter of investments into rail tracks instead of highways for realizing this mitigation option in the transport sector. Another option for decarbonizing the transport sector was to use biofuels. The COALOFF & CCS & BIO+ scenario illustrates that in such a world, the light green mitigation

cost curve is significantly lower. However, the use of biofuels is an ethically controversial issue. One has to add that we do not consider greenhouse gas emissions from land use change, so total greenhouse gas emissions could be eventually higher.

Finally, consider the two bottom mitigation cost curves in Graph 2. The lower one in light blue represents a structural development in Germany that enables all considered "extra" mitigation options. Notice how the economic feasibility frontier corresponding to a 90% CO_2 emission reduction target in 2050 as compared to 1990 levels is at 1% GDP losses. This makes a large difference to the respective economic feasibility frontier of the REFERENCE scenario at 4 % GDP losses. If we refrain from assuming the strong efficiency growth rates for final energies and energy services due to reasons discussed before, then the feasibility frontier was still at 2% as illustrated by the dark green mitigation cost curve. Each "extra" mitigation option does its share in keeping economic costs low, the relative reduction in GDP losses as compared to the REFERNCE scenario are indeed additive. These findings illustrate the strong impact of framing conditions on the economic feasibility of ambitious mitigation targets.

4   Conclusion

The possibilities for decarbonizing the German energy system over the next decades as a contribution to solving the global problem of anthropogenic climate change are numerous; technological mitigation options are available in the industry, residential, commercial and transport sector. Graph 3 once more presents the REFERENCE and ALL OPTIONS mitigation cost curve, this time with a technological feasibility frontier chosen for a very ambitious target of 90% CO_2 emission reduction versus the 1990 level, illustrating that the economic window of opportunity for ambitious mitigation is indeed wide. The assumptions behind the ALL OPTIONS scenario are, however, bold in the sense that a development path of the German energy system that fulfills all the assumptions implied significant structural breaks as compared to the past decades. Reflecting on the nature of the technological mitigation options that are exploited in the ALL OPTIONS scenario leads to the conclusion that all actors within the German energy system needed to make an effort to contribute to the CO_2 emission reduction objective. Ideas on how to achieve that are for example credible carbon policies pursued by the German government for stimulating investments of firms into low-emission technologies (Brunner et al., 2011) or small and medium scale governance units, linked through information networks and monitoring for reaching actors at all levels, from the individual over the family to the firm (Ostrom, 2009).
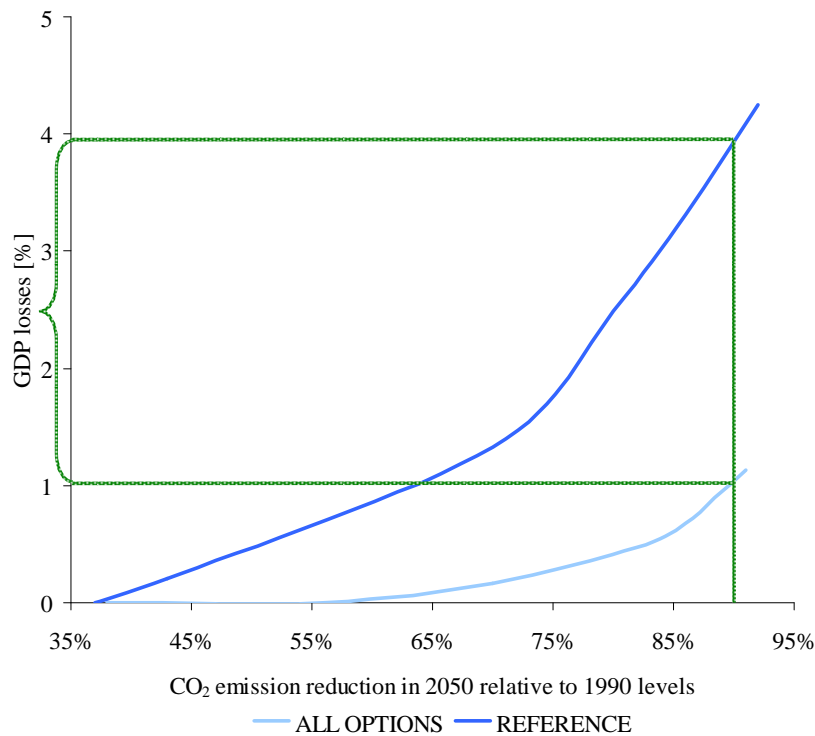
Graph 3. Mitigation cost curves of the German energy system for the two extreme scenarios that emerge from the discussion of framing conditions in Section 2.2. The ALL OPTIONS scenario assumes that all framing conditions develop in such a way that "extra" mitigation options are enabled. The REFERENCE scenario represents the case for which none of the "extra" mitigation options are available. The technical feasibility frontier set at 90% indicates that the incurred mitigation costs for such a target range between 1% and 4 % GDP losses.

Independent of how the diffusion of low-emission technologies will ultimately be induced by policymakers, the technological mitigation options are at hand or are in a relatively advanced stage of development and are ready to be deployed on a large scale. This analysis has shown that combinations of individual technological mitigation options do have the effect of enhancing the economic feasibility of ambitious mitigation targets. In sum, there is no silver bullet for mitigation and decisions on which mitigation options to pursue are subject to societal choice.

Acknowledgements

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