The Effect of Near-Term Climate Policies on the Achievability of Ambitious Long-Term Climate Targets

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Abstract

To keep the risks of climate change in check, the international community has agreed on the long-term target of limiting the increase of global mean temperature to no more than 2 °C above pre-industrial levels. This target is, however, so far not underpinned by commensurate near-term policy measures. Given the commons nature of the climate problem, the solution will eventually require concerted actions on the international level. To this end, negotiations have been conducted under the United Nations Framework Convention on Climate Change, but so far only made little progress towards tangible emission reductions consistent with the 2 °C limit. Instead, policy initiatives enacted so far have been regionally fragmented, incomprehensive and generally not ambitious enough to reach the stated 2 °C targets in a cost-effective manner.

Starting from this observation, this dissertation aims to answer the following three main questions: 1. What are the implications of a further delay of comprehensive climate policies? 2. What are the crucial determinants of adverse lock-ins and path-dependencies in the energy system induced by delayed action? 3. Which policy portfolio can keep the door to achieving ambitious targets at moderate costs open?

The answer to the first question is an important prerequisite to informing policy makers about the appropriate policy stringency today, weighing current and future risks and opportunities against each other. To provide a comprehensive evaluation, our analysis not only considers the traditionally used aggregated cost metric, but complements it with three other metrics that better represent the distributional and dynamic dimension of the problem. The answer to the second question helps to identify the most adverse impacts of delayed climate policies on the energy system’s climate change mitigation potentials. It thus also informs the choice about priorities for policies to bridge into a low-carbon future, as addressed in the third question. The idea here is to go beyond a one-dimensional option space of more or less near-term policy ambition, but to explore to which extent different policy instruments have a beneficial effect beyond their near-term effect on emissions, thus helping to keep long-term targets within reach. As recent experience has shown, governments have much less difficulty to implement technology policies than to implement carbon pricing. Therefore we analyze different policies regulating high-carbon and supporting low carbon technologies as well as a reform of subsidies and taxes for fossil fuels. Beyond the evaluation of the individual effects of these policies, an important contribution is to quantify the interactions among these instruments, as well as the interactions of these with two carbon pricing mechanisms, a carbon tax and a cap-and-trade scheme.

The research presented here is mainly based on the analysis of quantitative scenarios of large scale detailed numerical models of the global energy-economy system. This dissertation makes use of both the detailed analysis of larger number of scenarios produced from one model as well as the comparative analysis of harmonized scenario sets across different models. Five different research articles published in peer-reviewed scientific
journals form the core five chapters of this thesis, preceded by an introduction chapter laying out the wider background and methods. A discussion with the overall conclusions from the aggregate research plus an outlook to future research concludes.

Keywords: Climate change mitigation; Policy analysis; Delayed action; Carbon pricing; Technology policies
Zusammenfassung


Zusammenfassung

in einem Modell als auch aus der vergleichenden Analyse harmonisierter Szenariensätze in verschiedenen Modellen. Nach einem Einleitungskapitel, das Hintergrund und Methoden einführt, bilden fünf verschiedene Forschungsaufsätze, die in begutachteten Wissenschaftszeitschriften veröffentlicht wurden, die fünf Kernkapitel dieser Arbeit. Abschließend folgt darauf eine übergreifende Diskussion der Ergebnisse und Schlussfolgerungen, sowie ein Ausblick auf mögliche weiterführende Forschungsfragen.

Schlagworte: Klimaschutz; Politikanalyse; Verzögerte Klimapolitik; Emissionsbepreisung; Technologiepolitiken
## Nomenclature

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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AEII</td>
<td>Autonomous energy intensity improvement</td>
</tr>
<tr>
<td>AFR</td>
<td>Sub-Saharan Africa</td>
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<td>AMC</td>
<td>Aggregated mitigation costs</td>
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<td>AR5</td>
<td>Fifth Assessment Report of the IPCC</td>
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<tr>
<td>BAU</td>
<td>Business as usual scenario</td>
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<tr>
<td>BECCS</td>
<td>Bioenergy use combined with CCS</td>
</tr>
<tr>
<td>C&amp;L</td>
<td>Combined CM and LCS plus tax and subsidy reform</td>
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<tr>
<td>CBA</td>
<td>Cost-benefit analysis</td>
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<td>CCS</td>
<td>Carbon capture and storage</td>
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<tr>
<td>CEA</td>
<td>Cost-effectiveness analysis</td>
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<tr>
<td>CHN</td>
<td>China</td>
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<tr>
<td>CM</td>
<td>Coal moratorium</td>
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<tr>
<td>CMV</td>
<td>Carbon market value</td>
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<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
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<tr>
<td>CO₂e</td>
<td>CO₂ equivalent</td>
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<tr>
<td>COP</td>
<td>Conference of the Parties to the Convention</td>
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<td>CSP</td>
<td>Concentrated solar power</td>
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<tr>
<td>CV</td>
<td>Carbon value</td>
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<td>EEM</td>
<td>Energe-economy-climate model</td>
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<td>EPI</td>
<td>Energy price increase</td>
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<tr>
<td>EPX</td>
<td>Energy price increases</td>
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<td>EU</td>
<td>European Union</td>
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<td>EUR</td>
<td>Europe</td>
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<td>FE</td>
<td>Final energy</td>
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<td>GDP</td>
<td>Gross domestic product</td>
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<td>GE</td>
<td>General equilibrium</td>
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<td>GHG</td>
<td>Greenhouse gas</td>
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<td>GWP</td>
<td>Gross world product</td>
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<td>H₂</td>
<td>Hydrogen</td>
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<tr>
<td>IAM</td>
<td>Integrated assessment model</td>
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<td>IND</td>
<td>India</td>
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<td>INDC</td>
<td>Intended nationally determined contribution</td>
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<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<td>JPN</td>
<td>Japan</td>
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<td>LAM</td>
<td>Latin America</td>
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<td>LCS</td>
<td>Low-carbon support</td>
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<td>LTC</td>
<td>Long-term costs</td>
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<td>MAC</td>
<td>Marginal abatement cost</td>
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<td>MEA</td>
<td>Middle East and Northern Africa</td>
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<tr>
<td>OAS</td>
<td>Other Asia</td>
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<td>PE</td>
<td>Partial equilibrium</td>
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<td>POL</td>
<td>Policy scenario</td>
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<td>PV</td>
<td>Photovoltaics</td>
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<td>R&amp;D</td>
<td>Research and development</td>
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<td>REF</td>
<td>Reference scenario</td>
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<tr>
<td>ROW</td>
<td>Rest of the world</td>
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<td>RUS</td>
<td>Russia</td>
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<td>SE</td>
<td>Secondary energy</td>
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<td>STC</td>
<td>Short-term costs</td>
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<tr>
<td>TGR</td>
<td>Transitional growth reduction</td>
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UNFCCC  United Nations Framework Convention on Climate Change
USA  United States of America
Chapter 1

Introduction

This thesis is the outcome of three years of inter-disciplinary research into the interrelation of near-term climate policies and long-term mitigation targets. The novel scientific contribution of this work is presented in five research articles, reproduced here as Chapters 2 to 6. This introductory chapter serves four main purposes, each mainly addressed in a separate subsection: i) it explains the motivation of the research and its policy relevance; ii) it elaborates on the academic state of the art concerning economics and policy instruments of climate change mitigation; iii) it documents the main methods employed for the analysis, including a comparison with alternative methods found in the literature; and iv) it explains the overarching research questions and details how they are tackled in the five individual journal publications.

1.1 Motivation: Current State of Climate Policy

"All this will not be finished in the first 100 days. Nor will it be finished in the first 1,000 days, nor in the life of this Administration, nor even perhaps in our lifetime on this planet. But let us begin."

Excerpt from the inaugural speech of John F. Kennedy on January 20, 1961 (Kennedy, 1961)

Although Mr. Kennedy referred to different global challenges half a century ago, the humbleness expressed in his second sentence as well as the call for action expressed in the last four words fit quite well to the problem of climate change mitigation. Furthermore, the contrast between long-term aspirations and short-term action is a fitting theme for this thesis that sets out to contribute exactly to the understanding of the impact of the latter on the former: What is the effect of short-term climate policy action on the achievability of long-term targets? What constitutes ‘beginning’ to tackle the climate problem, in contrast to further procrastination?

The scientific understanding of the climate system has progressed significantly over the last decades. The latest, fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) states that the global mean surface temperature since 1951 has increased by a rate of 0.12 °C per decade and that this observed warming is extremely likely attributable to the anthropogenic increase in greenhouse gas (GHG) concentrations.
Furthermore, projections find a considerable further increase of warming and associated sea level rise over the course of the 21st century, even under the most optimistic emission scenarios considered. Currently, limited impacts on natural and human systems attributable to climate change can already be observed and climate-related risks are projected to increase strongly if warming continues (IPCC, 2014a).

In response to earlier similar insights from the first assessment report of the IPCC, the international community has already in 1992 formulated the goal to “prevent dangerous anthropogenic interference with the climate system” (United Nations, 1992). A first attempt to translate this formula into concrete actions to tackle the collective action problem of reducing emissions was the Kyoto Protocol (UNFCCC, 1998; Weyant and Hill, 1999). It foresaw legally binding reduction targets for only a subset of countries, the so-called Annex I countries, some of which never ratified the protocol. Although most ratifying countries did meet their targets for the first commitment period 2008-2012 and a second commitment period for the years 2013-2020 is currently underway (UNFCCC, 2012b), the ever smaller share of global emissions covered highlights the inadequacy of the protocol.

The inability to agree on a more comprehensive framework led to the failure of the 15th conference of the parties (COP) in Copenhagen in 2009. Instead of an agreement, several but not all parties of both the Annex I and non-Annex I country groups have unilaterally put forward pledges of mitigation action in the so-called Copenhagen Accord that was endorsed by the UNFCCC in subsequent COPs. Furthermore, the ultimate goal of the convention (see above) has been further specified “to hold the increase in global average temperature below 2 °C above pre-industrial levels” (UNFCCC, 2012a). Formally called the “Durban Platform for Enhanced Action”, the current plan at the UNFCCC level is to arrive at an agreement at COP 21 in Paris in December 2015 that would enter into effect in 2020. Due to the nature of negotiations between nearly 200 sovereign countries with very diverse interests, the outcome of this process is highly uncertain. The latest decisions at UNFCCC conferences indicate an increase in geographical coverage at the expense of legal binding force as general trend, resulting in a “pledge and review” paradigm of global climate policy as laid out in the Copenhagen accord.

As the outcome of the last meeting, COP 20 in LIMA, the Lima Accord calls on all countries to present “intended nationally determined contribution” (INDC) to the UNFCCC secretariat in the course of 2015, so that these can be taken into account for the negotiations before and at COP 21. An institutionalized assessment of the relative stringency of INDCs of different countries was opposed by a number of countries and is therefore not part of the Lima Accord. The secretariat is however requested to “[p]repare by 1 November 2015 a synthesis report on the aggregate effect of the intended nationally determined contributions communicated by Parties by 1 October 2015” (UNFCCC, 2014). This assessment will be difficult to perform, not only because of the short time but also because parties are not required to include quantifiable information to their INDCs and in the past even quantified targets have been ambiguous, e.g. targets specified as improvements with respect to a non-specified baseline.

In the five years since Copenhagen, the scientific understanding required for performing such an impact assessment has improved considerably. The immediate scientific response to the developments in and after Copenhagen was to test whether or not the unilaterally pledged emission reductions would add up to the mitigation action as foreseen in
long-term scenarios compatible with the endorsed 2 °C. As a result, an “emissions gap” between the global emissions level likely resulting from the pledges and the lower average emission level observed in optimal mitigation scenarios reaching 2 °C was identified (Rogelj et al., 2010, 2011; den Elzen et al., 2012). By itself, the finding of an emissions gap is insufficient for informing about the achievability of the 2 °C target, as well as the economic and environmental impact of such a deviation from optimal emission reduction pathways.

A focus of recent work, including the following chapters, has therefore been on studying the economic implications of reaching certain climate targets in “delayed action” scenarios instead of by following the traditionally considered optimal or immediate scenarios (Riahi et al., 2015; Kriegler et al., 2013b; Rogelj et al., 2013). As illustrated in Figure 1, the delayed action scenarios assume moderate policies representative of current pledges for a certain period of time (mostly until 2020 or 2030), followed by the unanticipated increase of policy stringency to be consistent with a long-term target. By varying the stringency as well as the policy instruments during the first policy period, the research performed for this thesis and by others has identified various consequences of near-term policy choices. The benefit of a profound understanding of these consequences lies a) in the weighing of the risks and costs of sub-optimal policies with the (political) costs and risks of implementing more stringent policies already in the near-term and b) in the identification of alternative measures that avoid the worst consequences of further delay if comprehensive policies are unattainable now for political reasons.

![Figure 1: Illustration of different policy scenarios. The solid black line between the green and blue line mark the ‘emissions gap’ in 2030.](image-url)


1.2 Academic Background

1.2.1 Economics of Climate Change Mitigations

Economics has been a very important tool for assessing the impacts of different policy options, both ex-ante through modeling based on different insights of economic theory, as well as through the empirical evaluations of existing policies.

Various characteristics of the climate change problem pose considerable challenges to the application of established tools of economics. Unlike in most other public policy issues, very long time frames and the global context have to be taken into account, because CO₂ as the most important GHG mixes well in the earth atmosphere and remains there for decades to centuries. This means that causes and impacts of climate change are decoupled and do not coincide neither in time nor necessarily in space. This has two important implications. On the one hand, the long time frame implies that a standard method of public economics, cost-benefit analysis (CBA), is hardly useful for the analysis of climate change. This is chiefly because of the uncertainty about damages (Ackerman and Munitz, 2012) in the far future and the normative question of the appropriate discount rate (Stern, 2008; Arrow et al., 2014). On the other hand, the global commons characteristic (Hardin, 1968) implies that an appropriate analysis of the problem has to happen on the global scale. This not only raises questions of how to weigh welfare impacts when aggregating very poor and very rich regions (Kolstad et al., 2014) but also means that there is no straightforward connection between the analysis and subsequent decisions on and implementation of measures. This explains why the analysis presented in this thesis is centered on the global level, with only a very limited regionally differentiated analysis in Chapters 2 and 3. Furthermore, Chapter 6, though analyzing global policy mixes, takes the lack of global legislative bodies and the difficulties in reaching legally binding agreements implicitly into account by analyzing different second-best policy options that could easily be implemented in different forms in different regions.

As a result of the difficulties with CBA and mirrored in the working group structure of the IPCC, the analysis of the climate change problem has often been divided into the impacts, vulnerability and risk side on the one hand, often including adaptation, and the analysis of possible mitigation strategies on the other hand. For the latter, the separation from possible damages means that cost-effectiveness analysis (CEA) can be employed. While in CBA the appropriate climate target that maximizes aggregated welfare emerges endogenously from the analysis, CEA takes a certain (climate) policy target as given and computes the pathway with highest aggregated welfare that fulfils that policy target. This pathway is usually compared with a benchmark scenario without the target, often called business-as-usual (BAU). By design, fulfilling the target results in a welfare cost in optimization models, as the damages avoided through the mitigation measures are not taken into account. Since the evaluation of options is performed on the much narrower cost category, co-benefits in terms of factors not explicitly represented in the optimization of a CEA can be evaluated ex-post. As an example, Cherp et al. (2013) find that mitigation policies result in increased resilience and reduced energy security risks in the first half of the century.
This thesis employs CEA for a detailed exploration of the mid- and long-term implications of different short-term policy choices, differentiated both by stringency and instrument. Implicitly, we also make use of the possibility to complement CEA with analysis of co-benefits. In Chapters 2 and 6, we not only analyze the traditionally used consumption loss indicator that is tightly coupled to the optimization, but also analyze energy price and carbon value impacts as proxies for distributional impacts and institutional requirements (see Section 1.3.5).

The next section details economic findings about different policy instruments. Section 1.2.3 then gives a short overview of the models used for economic valuation and their findings with respect to climate change mitigation.

### 1.2.2 Policy Instruments for Climate Change Mitigation

#### Policy Experience

In parallel to the international progress or lack of it (see Section 1.1), many climate-related policies are being implemented on levels ranging from local, subnational, national to the regional (Somanathan et al., 2014). There are examples of emission pricing policies implemented either as carbon taxes or as emissions trading schemes (World Bank, 2014). Even more widespread is the adoption of sector-specific technology policies that have explicit or implicit connection to emission reduction efforts (Edenhofer et al., 2014). They include measures to promote certain low-carbon technologies and measures promoting minimum technology performance, either in terms of emission or energy efficiency (IEA, 2014; Edenhofer et al., 2014). They follow different policy instrument approaches, ranging from mere information campaigns, over financial incentives to legally binding mandates.

The interrelation between the international negotiations and policy initiatives on lower levels of governance is bi-directional. On the one hand, it is often argued that the international negotiations have to precede local instrument implementation. As the climate problem is the problem of a global commons (Hardin, 1968; Ostrom, 2010), a concerted effort seems necessary to overcome free-riding problems effectively. On the other hand, the willingness to accept mitigation obligations in international negotiations might benefit from own or other countries’ experiences with successful mitigation policies. Furthermore, in the light of the difficulties in international negotiations unilateral action is the only way for ambitious countries to immediately start emission reductions efforts. Another argument in favor of fragmented policy action is that the heterogeneity of initiatives is not only a disadvantage. The loss in static efficiency it represents might be worthwhile to accept as the variety of policy approaches enables policy learning and exchange of best practices, which might be efficiency enhancing in the long-term.

#### Academic Analysis

Classic economics recommends internalizing the externality of climate change by means of a pricing instrument, often referred to also as a market-based instrument. The theoretical justifications for such a policy response is that the pricing mechanism informs all actors in the different sectors of the economy and along the whole supply chains of
the externality so that the market can bring about the necessary mitigation options that are cheapest (Goulder and Parry, 2008). Not specifying any particular mitigation measures directly and having an economy wide equal price thus guarantees that the efficient solution is reached.

With full knowledge about the social costs of emissions, i.e. climate damages, and the costs of mitigation options, the regulator can choose between two fully equivalent market instruments. The first, a carbon tax, pegs the price whereas the other, a cap-and-trade scheme, pegs the quantity of allowable emissions and issues tradable permits for these. The symmetry between those two instruments breaks however, if the assumption of certainty and full information is relaxed. Weitzman (1974) showed that fixing the price rather than the quantity is the superior choice if the marginal mitigation cost function exhibits a higher curvature than the marginal damage function and vice versa.

However, as noted already by Weitzman, there are also many situations where the two approaches yield very similar results considering uncertainty, so that “non-economic factors” (Weitzman, 1974) have to be considered for making the choice. Reflecting this, a wealth of literature has since then scrutinized further considerations that can lead to an advantage for one of the instruments, e.g. negotiations on international agreements (Kornek and Marschinski, 2014; Weitzman, 2014), technology choice (Krysiak, 2008), stock pollution and dynamic settings, including discounting (Hoel and Karp, 2002; Newell and Pizer, 2003), and interactions with other policy instruments (Shobe and Burtraw, 2012; Goulder and Schein, 2013). During the last decade, both approaches have been implemented in various sectorally and geographically limited policy initiatives (World Bank, 2014). The experience with these implementations has shown that often specifics of design “may be as important as the choice between the two instruments” (Goulder and Schein, 2013) and different forms of hybrid solutions are implemented or discussed (Metcalf, 2009; Pizer, 2002).

Despite the efficiency advantages of pricing instruments predicted by economic theory, the majority of climate policies enacted over the last decade do not fall under this category (Somanathan et al., 2014). Instead, they follow the regulatory approach, mostly with a sectoral focus. In economic theory there has been a heated debate of whether or not this kind of policies might be warranted in addition to carbon pricing despite the efficiency disadvantage discussed above. Most scholars agree that this might be the case if other market failures beyond the climate externality are the predominant target of such policies (Jaffe et al., 2005; Bennear and Stavins, 2007; Lehmann, 2012). Examples are support policies for new technologies to tackle the problem of imperfect appropriability of innovations (Jaffe et al., 2005; Fischer and Newell, 2008) or efficiency standards to tackle underinvestment into efficiency measures caused by imperfect information or asymmetric incentives (Jaffe and Stavins, 1994; Gillingham et al., 2006, 2009). Another possible justification for regulatory policies discussed by some authors comes from different constraints e.g. lack of stakeholder support or limited administrative capacities (Bennear and Stavins, 2007) or high transaction costs (Lehmann, 2012).

Most of the studies above focused on the criterion of economic cost-effectiveness for the evaluation of different policies. Nevertheless, for a relevant assessment of the merits of different instruments, this criterion should be complemented by the environmental effectiveness, distributional impacts and political and institutional feasibility (Kolstad et al., 2014; Somanathan et al., 2014).
While many of the above mentioned insights come from analytical models or empirical evidence, there have been attempts to model the role of policy instruments and their interaction in numerical models with explicit representation of agents (Fischer and Newell, 2008; Kalkuhl et al., 2012, 2013, 2014). Thanks to this property, they produced relevant insight about different strategic considerations that have to be taken into account with respect to different policy instruments, e.g. the risk of a carbon lock-in (Kalkuhl et al., 2012). On the other hand, the employed models are rather coarse in their resolution of the energy system. Some of the basic supply side dynamics are nevertheless captured in a correct way (Kalkuhl et al., 2014), but the dynamics between different fossil and renewable energy carriers cannot be studied.

More detailed energy economy models (see Section 1.2.3) like those employed in this thesis (Sections 1.3.1 and 1.3.4) have traditionally not focused on detailed specifications of policy instruments beyond very generic pricing policies, either carbon taxes or emission caps implemented as explicit bounds on cumulative emissions. For regional models, there are some exceptions: Analyzing different EU policies and combinations until 2020, (Böhringer et al., 2009) find mixed results across models. For the example of the United States, Fawcett et al. (2014) evaluate the interactions of an economy-wide cap-and-trade and sector-specific regulatory policies until 2050 and find that the addition of regulatory policies to a cap-and-trade system lead to lower carbon prices but higher economic costs. The following section gives an overview about global models with rich energy system representation and their applications to questions of the economics of climate change and policy instruments.

### 1.2.3 Energy-Economy-Climate Models (EEMs)

Detailed energy-economy(-climate) models (EEMs) such as those employed in this thesis have been a very important method for the economic evaluation of different climate targets, which is reflected in the role of scenario results from such models in recent assessments (IPCC, 2014b; Clarke et al., 2014; UNEP, 2013).

#### Definition and Classification

There is no authoritative definition for EEMs and the boundaries to other numerical models like e.g. the numerical models mentioned above (Kalkuhl et al., 2012) are rather fuzzy. The same class of models is sometimes also called integrated assessment models (IAMs) which is especially problematic, as the same denomination is used for models like DICE (Nordhaus, 1992; Popp, 2004) or FUND (Tol, 1997) that do employ cost-benefit analysis (see Section 1.2.1) and usually have much coarser energy system representation.

Inspired by Krey (2014), we here define the group of models employed in this thesis (EEMs) by their output, namely by the fact that this class of models can produce somewhat detailed future scenarios of energy use and corresponding emissions and costs. The minimum requirement that is met by all those models is that they represent at least 10 different world regions, have time steps of 10 years or shorter, differentiate various fossil and non-fossil energy sources and at least track all CO_2 emissions from the energy system. Furthermore they at least account for all the costs of the energy system, so that one of the usual metrics for mitigation costs can be reported (either area under the curve of
marginal abatement cost, consumption loss, GDP loss or additional total energy system cost).

Various classifications based on different fundamental mechanisms underlying the model structure (e.g. optimal growth model, computational general equilibrium model, simulation model, etc.) can be done, although the increased existence of “hybrid” models that make use of different approaches at the same time tends to make these classifications more and more ambiguous. Two aspects of models that can be unambiguously stated and help to put some of the differences in results into perspective are the economic scope and the temporal solution strategy (Kriegler et al., 2015a). Whereas partial equilibrium (PE) models describe only a part of the economy and use exogenous assumptions for the sectors not represented, general equilibrium (GE) models represent the whole economy (although often in a rather coarse resolution) in an endogenous manner. Both model types can either be solved via recursive dynamic algorithms or using intertemporal optimization. The partial equilibrium and recursive dynamic approaches are generally less demanding computationally and therefore allow for more detail of the energy system. General equilibrium models have the advantage of capturing more interaction and feedback affects across sectors. Intertemporal optimization offers the computation of a dynamic efficient benchmark.

From the models used in this study, REMIND (see Section 1.3.1), MERGE-ETL (Kypreos, 2005), MESSAGE (Messner and Schrattenholzer, 2000), and WITCH (Bosetti et al., 2009c) fall under the category of intertemporal optimizing GE models, IMACLIM (Waśman et al., 2012) is a recursive dynamic GE model, DNE21+ (Akimoto et al., 2004) is a intertemporal optimizing PE model, and GCAM (Kim et al., 2006), IMAGE (Bouwman et al., 2006) and POLES (Criqui et al., 1999) are recursive dynamic PE models.

Based on the evaluation of four diagnostic indicators of model results, Kriegler et al. (2015a) propose a preliminary classification scheme into low, medium and high response models. This is ongoing work to which the analysis of model differences in Chapter 4 contributes.

Results

EEMs have in the past been used regularly for the evaluation of mitigation costs of different climate targets, employing cost-effectiveness analysis (see Section 1.2.1). Furthermore, the necessary energy system transformations for mitigation have been analyzed. The topics of this thesis have so far not been in the focus of studies with EEMs.

Regarding the interrelation between shorter-term policy stringency and the achievability of long-term targets, O’Neill et al. (2010) provide a relevant precedent in terms of the overall methodology, but their choice of 2050 as the reference period is not suitable to bridge the gap to the short-term policy discussions. Other earlier work on short-term targets has, probably due to the construction of the Kyoto protocol, focused more on participation of certain regions (Keppo and Rao, 2007; Clarke et al., 2009) instead of the level of short-term ambition. Therefore, assessments and studies after COP15 in Copenhagen in 2009 have first framed the analysis around the “emissions gap”, comparing the emission trajectories of optimal mitigation scenarios with projected emissions for the year 2020 (UNEP, 2010, 2011; Rogelj et al., 2010, 2011). More recently, parallel and partly connected to the work presented here, a few other studies have also contributed to the
understanding of the interrelationship between short-term policy stringency and achievability of long-term targets by also looking at scenarios with varied near-term emissions that all reach the same long-term target (Rogelj et al., 2012, 2013; Riahi et al., 2015). Based on these studies and the earlier ones contained in this thesis (Chapters 2 to 4), the latest, fifth assessment report of the IPCC (AR5) contains a detailed analysis of the implications of the timing of mitigation (Clarke et al., 2014, Sections 6.3.2.2, 6.3.6.4 and 6.4).

In terms of policy interactions, our work in Chapters 5 and 6 is not considered in the latest assessment as neither article has been accepted early enough. Therefore, the discussion in the AR5 (Clarke et al., 2014, Sections 6.3.6.5 and 6.5.1) cites only three studies from global EEMs with a focus on policy interactions. Guivarch et al. (2011) focus on the possible role of supporting labor policies for mitigation, (Waisman et al., 2012) explore interactions with infrastructure investment policies, and Marangoni and Tavoni (2014) analyse to what extent dedicated research and development (R&D) policies could be a short-term substitute for emission pricing policies. Beyond that, the findings from regional models or models with less energy system detail (as discussed in Section 1.2.2) are cited.

Although not directly mentioned in that context in AR5, a few other studies have also analyzed the implications of different policy instruments. Magné et al. (2014) study the interplay of a nuclear phase-out policy with a removal of fossil fuel subsidies. Kriegler et al. (2015b) and Marcucci and Turton (2014) analyze the energy system impacts of a moderate policy package including a technology policies but due to their scenario set-up do not separate and compare the specific impact of single policy instruments. Yet other studies have looked at the specific benefit for developing countries to commit to future emission targets and to invest into innovation in regionally fragmented policy regimes in which OECD countries act as first movers (Bosetti et al., 2009a; Richels et al., 2009).

1.3 Methods

This thesis aims to contribute to an understanding of the long-run consequences on climate change of short- to medium-term energy policy decisions. The main method employed is the analysis of quantitative scenarios generated with different numerical models of the global energy-economy-climate system as presented in the previous section. This subsection documents the relevant characteristics of the model REMIND that is used in Chapters 2 - 6 as well as methodological extensions to this model that were done to improve the analysis of this thesis. Furthermore, Section 1.3.4 explains the advantages and limitations of comparing results across different EEMs, as done in the comparative analysis in Chapters 3 - 5. Section 1.3.5 explains the rational for the different economic indicators used in Chapters 2, 3 and 6. For a critical discussion of these methods, we refer to Section 7.3 at the end of this thesis.
1.3.1 General Structure of the REMIND Model

General Structure

The analysis of this thesis builds in great part on the numerical model REMIND (Leimbach et al., 2010). The latest version 1.5 that is used in Chapters 2, 4, 5 and 6 is documented in detail in Luderer et al. (2013) while Chapter 3 uses version 1.4. For the analysis performed in this thesis, the ability to represent different energy related policies in the model (Section 1.3.2) as well as the representation of relevant inter-temporal linkages (Section 1.3.3) are crucial and discussed more intensively further down. The model also fulfills more basic prerequisites such as the full coverage in temporal, spatial and energy system dimension as well as the representation of the relevant inter-linkages along these dimensions.

![Diagram of the REMIND model](image)

**Figure 2:** The general structure of the REMIND model with the hard link of the macro-economic and the energy system module. One representative region is shown with bidirectional arrows indicating trade relations to a global pool. The orange arrows denote options for policy representation as developed and employed in this thesis. Bold letters denote optimization variables. Investment cost for some technologies are a function of cumulative deployment through learning curves with floor costs.

It spans the whole 21st century in 5-year time steps until 2060 and 10-year time steps thereafter. The global energy and economy systems are fully represented, disaggregated into 11 regions. Five of these (USA, China, India, Japan and Russia) are single countries whereas the remaining six regions are composed of various countries, with groupings based on both geographical proximity as well as homogeneity in terms of economic and energy system structure.
The supply side of the energy system is fully represented and is hard-linked to the economy in a two-way interaction (Figure 2): On the one hand, a composite of various final energy types is, together with macro-economic capital and labor a necessary input for the generation of output (GDP) in each region (see also Figure 3). The supply of final energy on the other hand incurs costs, represented on the primary, secondary and distribution level and composed of both investment, operation and maintenance costs, as well as fuel costs and taxes. In each time-step, each region has to fulfill a budget constraint, so that the total of output equals the sum of energy system costs, investment into macro-capital, consumption and the net of trade in a generic good. For the latter, the assumption is that each region has to have a balanced current account at the end of the modeling time horizon but can temporarily have net savings or debt with other regions.

\[
\sigma = 0.3 \\
\sigma = 3 \\
\sigma = 1.5 \\
\sigma = 1.3 \\
\sigma = \infty
\]

\[
\text{difficult} \\
\text{easy} \\
\text{Substitution}
\]

\[
\text{Transport} \\
\text{Av. & Bus} \\
\text{E. Train} \\
\text{Freight} \\
\text{H.2} \\
\text{LDV} \\
\text{Av. & Bus} \\
\text{BEV} \\
\text{H.2 FCV}
\]

\[
\text{Nonelectric} \\
\text{Power} \\
\text{Gas} \\
\text{Solids} \\
\text{Heat} \\
\text{Liquids} \\
\text{H2}
\]

\[
\text{Capital} \\
\text{Labour} \\
\text{Aggregated Energy} \\
\text{GDP}
\]

\[
\sigma = 0.5 \\
\sigma = 0.3 \\
\sigma = 0.3 \\
\sigma = 1.3
\]


REMIND is solved as a non-linear optimization model with perfect foresight, maximizing the intertemporal utility of each region’s representative household with full regional cooperation. It thus follows the approach of a neo-classical optimal growth model with endogenous savings rate (Ramsey, 1928; Cass, 1965; Koopmans, 1963; Barro and Sala-i Martin, 2004) and falls under the category of general equilibrium models (GE) with intertemporal optimization (see Section 1.2.3). The utility is a logarithmic function of per-capita consumption and a pure rate of time preference of 3% discounts future utility. The balanced current account condition is realized via the Negishi approach (Negishi, 1960, 1972).

**Previous Applications**

In the past, the main application of the model was to analyze optimal energy system transformation pathways under specific climate targets, i.e. for cost-effectiveness analysis (see Section 1.2.1). Thanks to the possibility of hard-coupling a simple climate module
to REMIND, targets can be specified both on climate variables like concentration, forcing or temperature as well as on cumulative emissions budgets. Most analysis so far focused on questions of overall mitigation costs and the underlying energy system transformation requirements. For the analysis of mitigation costs, the consumption or GDP of a scenario with a given target is compared with a benchmark scenario without any policy, usually called business-as-usual (BAU) (Leimbach et al., 2010). A subset of studies analyzed, how these costs depend on assumptions on technology availability (Kriegler et al., 2013a; Bauer et al., 2012) and/or macro-economic assumptions like population, GDP or energy demand trajectories. With respect to the energy system transformation, the policy-induced changes of the energy system as a whole (Luderer et al., 2012b) or specific sub-sectors are analyzed, like the nuclear (Bauer et al., 2012), solar (Pietzcker et al., 2014b), fossil (Bauer et al., 2013), bioenergy (Klein et al., 2013) or the transport sector (Pietzcker et al., 2014a).

1.3.2 Representation of Policy Instruments in EEMs

The central innovation of this thesis is to analyze the effects of mid-term policies on the achievability of long-term climate targets. This required the methodological innovation of improving the representation of energy-relevant policies, especially taxes and subsidies in a long-term optimization model with considerable energy system detail. Furthermore, to arrive at more meaningful policy recommendations, the scope of climate policies was extended and refined, including pricing policies as well as technology policies.

Final Energy Taxes and Subsidies

Taxes and subsidies for final energy use have a considerable impact on the direct consumer prices and therefore are a strong driver for the overall level of energy demand and the composition of different fuels for fulfilling this demand. In order to model the effects of price changes due to climate policies on demand, these pre-existing distortions have to be considered in a model. As part of this thesis, regionally differentiated tax and subsidy levels were implemented on final energy uses $f$ (for the documentation of data sources see Chapter 5). They are implemented in a budget-neutral way: In each solution iteration $i$, the net revenue $v_{rti}$ for region $r$ and time step $t$ is the difference between the paid taxes and the revenue of the previous iteration (Equation 1.1). This way, the net revenue that is a summand in the budget equation converges iteratively to zero. Therefore the taxes do not have an effect on the available budget, but the optimization is subject to the distorting marginal effect of taxes and subsidies.

$$v_{rti} = \left( \sum_f \tau_{rf} \cdot a_{rf} \right) - v_{rti-1}$$  (1.1)

Emission Pricing Policies

This thesis has also extended the range of emission pricing representations. The dominant form of climate policies represented so far - generally in energy-economy-models
but also in REMIND - has been some kind of economy-wide emissions control. This is either done by explicitly applying tax rates on the emission of greenhouse gases, typically increasing exponentially at a fixed yearly growth rate of 5%. Alternatively the amount of allowable emissions is restricted, such that the optimization yields shadow prices for emissions that can be interpreted as the implicit prices. The latter is either done by explicitly defining allowable emissions budgets for certain periods or, in models coupled with a climate system representation, by imposing limits on climate variables like atmospheric concentrations, forcing or global mean temperature that correlate well with emissions budgets (Meinshausen et al., 2009).

For Chapters 2 and 3, we implemented a regionally differentiated moderate near-term policy. The representation aims to mimic the real-world fragmentation of near-term climate policies as documented in the pledges first put forward as part of the Copenhagen Accord (UNFCCC, 2009). The implementation in the model introduces regionally differentiated multi-gas emissions budgets for the periods 2010-2020, 2025-2050 and 2055-2100. Whereas the first of these budgets is directly deduced from announced pledges, the budgets for the following periods are defined by assuming regionally differentiated yearly emission reduction rates. Banking of emission permits is allowed but no borrowing. Furthermore, after 2020 regions can trade permits, but for Annex I regions, the total of permit imports is limited to 20% of their respective mitigation burden, i.e. the difference between baseline emissions and allowances.

Another important innovation in my thesis is the modeling approach to mimic policies that aim at certain emission levels for one specific year (see Chapters 4 and 6). Many real world policy targets are formulated in terms of emission reductions in a specific target year, for example the 20% reduction target of the European Union for 2020. Due to the intertemporal optimization, just imposing an upper bound on emissions in one model period is not a satisfactory representation of such a policy, as the anticipation of no further emission control later on has a relevant impact on the kind of emission abatement performed to reach the yearly target. As it is plausible to assume that such policy targets are perceived to indicate a continuation of emission pricing at a similar ambition level, we implement exponentially increasing carbon tax scenarios in which the tax level is iteratively adjusted such that the yearly target in the specified year is met. The algorithm for the iterative adjustment of the tax level $\tau$ as shown in Equation 1.2 makes sure that both high and low tax values are reached in a limited number of iterations.

$$\tau_i = \tau_{i-1} \cdot \min \left( \frac{\text{GHG}_{i-1}}{\text{GHG}_{\text{target}}}^8 , 2 \right) \quad (1.2)$$

In a very similar fashion, the formulation of the long-term policy target in Chapters 4 and 6 was implemented as an iteratively adjusted long-term multigas budget. The scenario protocol of the AMPERE study (Riahi et al., 2015) defined a CO$_2$ emissions budget for the 21st century but demanded that other emission species be priced equivalently. The most straight-forward way to implement this is to define a multigas budget, using global warming potentials for the conversion of emission quantities into CO$_2$-equivalents (CO$_2$e). As
there is a nearly linear relationship between a given CO\textsubscript{2} and multigas budget, a simple linear adjustment algorithm (Equation 1.3) is used.

\[ BudgCO_2^i = BudgCO_2^{i-1} - Budg_{target}^{GHG} \cdot Budg_{target}^{GHG} \] (1.3)

Technology Policies

In order to accommodate the complexities arising from the detailed energy system representation and the intertemporal optimization, REMIND has a rather simple representation of the economy with just one representative household per region. Therefore, unlike other studies with more actor detail which comes at the cost of lower energy detail (Kalkuhl et al., 2013, 2014), this thesis uses a rather generic representation of technology policies. In REMIND it is not possible to specify the direct policy intervention with respect to market agents, such as production subsidies like feed-in-tariffs or tax breaks, portfolio standards or performance standards. The approach here is therefore rather to prescribe only the effects of such policies: For low carbon energy technologies, a lower bound on the deployment is set, whereas an upper bound is applied to certain emission intensive technologies. This modeling choice implies that governments have the means to either impose such targets directly or else have adaptive pricing instruments available, comparable to the “breathing cap” in Germany (Lehmann et al., 2012).

Another implication of the modeling framework is that distributional impacts of the technology policies such as windfall profits to owners of suitable land areas cannot be analyzed. Whereas the upper bound on carbon intensive technologies leads to higher energy prices, the lower bound on low-carbon energy leads to a slight depression of energy prices. The reason for this is that the additional production of low-carbon energy partly replaces some energy supply at the margin. For niche technologies, this is a realistic result, as subsidies for early deployment support of novel technologies are often financed by the general public budget. Therefore the support for battery-electric vehicles, gas-fired power generation with carbon capture and storage (CCS) and biofuel production with CCS was implemented in the simple form of a lower bound without any adjustment to compensate for the price depressing effect. By contrast, for technologies that have already gained a relevant market share so far, most support policies implemented by governments lead to an increase of consumer prices, for example by using portfolio standards or by financing feed-in tariff payments through a premium fee collected from consumers. Similar to this latter approach, we here implement a regionally differentiated consumer premium fee \( p_r \) that pays for the additional costs resulting from the minimum requirements on wind, photovoltaics (PV) and concentrated solar power (CSP) electricity generation, as described by Equation 1.4, with \( E^*_r \) being the total electricity consumption in region \( r \), \( D_{r,n}^* \) and \( D_{r,n} \) the deployment for technology \( n \) in the scenarios with and without technology policy, and \( c_{r,n} \) the levelized cost of electricity.

\[ p_r = \frac{1}{E^*_r} \sum_n (D_{r,n}^* - D_{r,n}) \cdot c_{r,n} \] (1.4)
1.3 Methods

Note that this formulation makes sure that the premium fee vanishes if the lower bound is not binding, as the expression in parenthesis becomes zero in this case.

1.3.3 Representation of Myopia in Intertemporal Optimization Models

One important methodological component of our analysis is the missing anticipation of later climate policies in scenarios of delayed climate action. This thesis has improved on the representation of myopia in three main characteristics: (i) we implemented scenarios with moderate policy ambition for an initial period of delay and a stringent implementation of climate targets later on, (ii) introduced the option of prematurely retiring existing capacities, and (iii) improved on the technical implementation of constraining the optimization for initial periods on results of previous runs, leading to higher reliability and shorter run time.

Implementing Moderate Climate Policies without Anticipation of Later Increases in Policy Stringency

Due to the intertemporal optimization, the model response in early time steps is generally dependent on policy settings in later time-steps, i.e. future policies are fully anticipated. In order to avoid this anticipation, one can in principle either perform runs with shorter modeling time horizons as done by Keppo and Strubegger (2010) or, as done here, runs with the full modeling time horizon but without climate policies in the future. In a second stage, the results of such a pre-run can then be used to constrain the model for a certain period at the beginning of the modeling time frame, with free optimization of model variables only starting thereafter. The approach of a shorter time frame is difficult to realize in our framework, as the scarcities in the future drive the short-term price developments to a large extents. Therefore, one would need to translate the long-term potentials of exhaustible resources into equivalents for shorter time-frames, which is not straightforward to do. Not doing this completely changes the baseline scenario developments (Keppo and Strubegger, 2010) so that such scenarios cannot directly be compared with scenarios with full intertemporal optimization.

The approach we chose therefore is to use scenarios in which the near-term climate policy regime is extrapolated into the future for the remainder of the model’s time horizon, implicitly assuming that investors assume that current trends persist. This approach is trivial, as long as for the period of the delay no climate policy at all is assumed to be in place, as the baseline scenario can then be used to constrain the optimization for the period of delay. Previous studies have followed this approach, either for all model regions simultaneously (Luderer et al., 2012a; Jakob et al., 2012; Rogelj et al., 2013), or only for specific regions in scenarios with regionally fragmented climate policies (Clarke et al., 2009). If however, certain moderate policy initiatives in the near- to mid-term are to be considered, it is of crucial importance to find a plausible extrapolation for these for the long-term. The extreme possibilities are to a) not consider any climate policy in the long-term or b) allow for anticipation of future increases of policy stringency. Whereas the former approach would result in the highest degree of carbon lock-in and hence the most severe implication of a policy delay, the latter approach would lead to much lower
carbon lock-in. Previous literature indicates that the cost difference resulting from these two alternatives can be substantial, with anticipation lowering the cost of delay by up to 50% (Clarke et al., 2009; Blanford et al., 2009; Bosetti et al., 2009b). We here explore two options that are somewhat in between: An extrapolation of policy ambition based on constant emission intensity improvement rates, implemented as emissions budgets (Chapter 2 and 3) and carbon taxes increasing with a constant yearly growth rate of 5% (Chapters 4 and 6, see also Section 1.3.2).

**Early Retirement of Capacities**

In the detailed analysis of scenarios with unanticipated changes of policy stringency the modeling assumptions on the lifetimes of technology capacities are crucial. Here, unlike in traditionally analyzed immediate policy action or baseline scenarios, it is important whether or not capacities built just before a sudden change of the policy regime have to continue operation or can be retired before the end of their technical lifetime. In other models, the whole range of possible representations from no retirement option to immediate full retirement can be found (see Chapter 4). For the REMIND model, we implemented premature retirement with a limit on the rate at which capacities can be taken off the market. This approach takes the flexibility that early retirement can offer into account, but at the same time reflects real-world barriers that exist for the sudden complete shut-down of whole power plant fleets. Possible barriers not explicitly represented in the model exist both on the socio-political side (e.g. distributional issues and the bargaining power of vested interests) as well as on the technical side (e.g. the time requirements for restructing the power grids to changed generation mixes). For each technology, an increasing fraction of the capacities that are within their technical lifetime can be shut down. In order to have a computationally lean representation, vintage stocks are not differentiated, so that all vintages are subject to the same premature retirement ratio. This ratio is allowed to increase linearly by 4% per year, so that a full retirement is only possible after 25 years. “Cold reserves” are ruled out, so the ratio of retired capacity must increase monotonously.

**Sequential Scenario Run Implementation**

On a more technical level, we improved the implementation of second stage scenario runs that follow the trajectory of a previous run for a certain initial time period. Previously, this was done by fixing only a small number of variables, namely the emissions, capacity additions, consumption and capital investments for the initial time steps. Even though this gave satisfactory results when looking at time series of most variables, it created some problems for the reporting of prices based on the marginal value of variables. Furthermore, the size of the numerical problem was not reduced compared with a run with the full modeling time frame, leading to issues with long run time and infeasibilities.

Our innovation was to introduce a new dynamic subset (McCarl et al., 2014) of the time periods set. This subset \( t(t_{tot}) \) is reduced for sequential runs, only including the free time steps starting with the first time step \( c_{startyear} \) after the initial period that is taken from a previous run (Equation 1.5). Furthermore, all values of variables for the initial time
periods are fixed to their respective value in the preceding run and all marginal values are read in for correct reporting of prices.

\[ t(t_{\text{tot}}) = \{ t_{\text{tot}} : t_{\text{tot}} \geq c_{\text{start year}} \} \]  

(1.5)

This innovation has several advantages. It helps for the structural clarity of the model code. Most equations only describe restrictions that link several variables of one time step with each other. In the new implementation, these equations are defined on the reduced time subset \( t \). The remaining equations feature some sort of intertemporal relationship, i.e. they link variables in one period to values of the same or other variables in one or several previous time steps. This equations are still defined over the full modelling time set \( t_{\text{tot}} \), but restricted to start with the first free time step. Examples are the capital motion equation describing the development of capital stocks due to investments and depreciation, or cumulative emissions budgets. Another advantage is that the size of the optimization model is substantially reduced, resulting in shorter run-time and higher stability.

### 1.3.4 Model Intercomparison Exercises

Given the inherent limitations of long-term modeling (see Section 7.3), the intercomparison of results from various models is an established method to increase the understanding about robust features and key uncertainties. It has been employed both for broader assessments (Clarke et al., 2014; UNEP, 2013), as well as in large-scale research projects tackling specific research questions, like EMF22 (Clarke et al., 2009), ADAM (Edenhofer et al., 2010), RECIPE (Luderer et al., 2012a), AME (Calvin et al., 2012), LIMITS (Kriegler et al., 2013b), AMPERE (Riahi et al., 2015; Kriegler et al., 2015b) or EMF 27 (Kriegler et al., 2014).

In view of the inherent difficulties in accurately modeling human decision and the evolution of social systems, the validation of models of the energy-economy system is even more challenging than the validation of models of natural systems (Oreskes et al., 1994). Evaluation, including sensitivity analysis, (Schwanitz, 2013) and characterization (Kriegler et al., 2015a) of models as well as performance tests for the past (Tol, 2014) can be useful tools to better understand model differences and the underlying reasons, but they will not be able to allow for accurately weighing models with respect to the trustworthiness of their future results. Therefore, sensitivity analysis and the comparison of results across different models that are structurally different and use different values for uncertain parameters is the only practical way to identify robust as well as uncertain insights about future energy system developments. Nevertheless, this also comes with some important caveats (Section 7.3) and the robustness of a particular result across different models should not be mistaken as a proof of its general validity.
1.3.5 Indicators for Assessing Mitigation Challenges

While the previous subsections have elaborated on the methodological extensions for the production of self-consistent scenarios of future energy use and emissions, this section briefly describes the innovation in the analysis of such scenarios.

In ‘cost-effectiveness analysis’ (CEA, see Section 1.2.1) the cost of achieving a given target is considered, and optimization models typically minimize this cost. As the considered target usually is an aggregate long-term target like temperature or forcing in 2100, different global long-term metrics were traditionally used to operationalize the cost. In the REMIND optimization, temporally and regionally aggregated welfare as a function of consumption is maximized (i.e. the loss in welfare is minimized in policy scenarios). By default, welfare effects are reported in terms of regionally and temporally aggregated consumption losses discounted at 5% p.a.. Such consumption losses can be expressed in net present value, or as a share of aggregated GDP or consumption, and thus allow for comparisons across models. This metric is also widely used in IPCC assessments, including AR5 (Clarke et al., 2014, Section 6.3.6).

Initial analysis of delayed action scenarios revealed that this cumulated consumption loss indicator is rather insensitive to a delay of climate policies. A crucial limitation of the temporal aggregation is that it masks important changes in the temporal distribution of costs as lower costs in the near-term compensate the substantially increased costs in later decades which are furthermore subject to discounting. To capture the effect of rapidly increasing costs in the decade after adoption of more stringent climate policies, Chapters 2, 3 and 6 complement the cumulated cost indicator with an indicator of the derivative of the consumption or income loss. In order to be in units that can easily be related to common metrics like e.g. yearly output growth, it is expressed as the transitional reduction of consumption/output growth per year or decade.

Furthermore, the aggregate cost is an insufficient indicator for the political feasibility of a certain climate target. A cost of a few percentage points might seem manageable. Nevertheless, such a low aggregate cost can still imply much higher relative costs for certain groups of a society. A rigorous assessment of such distributional challenges of mitigation pathways would require the disaggregated modeling of different income groups instead of just one representative household per region. So far, this is not possible for an EEM with detailed energy system, both for computational reasons and for lack of knowledge about long-term drivers of inequality. As an alternative, we analyze a proxy metric, the total value of carbon. Stringent climate policies imply the devaluation of the rent of fossil resources and at the same time the creation of an even bigger rent in the form of the value of allowable emissions to the atmosphere (Bauer et al., 2013). The size of this rent is therefore a good indicator for the distributional challenge and institutional requirements for distributing costs across income groups and countries. For delayed action scenarios, the same issues arising from the temporal aggregation of consumption losses apply to the carbon value indicator. We therefore complement this long-term indicator with the energy price increase after adoption of the stringent target. This indicator also has the advantage of being comparable in units to common historical data and on the other hand also serves as a proxy for distributional challenges, as energy price increases also create losers and winners within society.
The algebraic formulations for the calculation of the four used indicators (cumulated consumption loss, reduction of consumption growth rate, total value of carbon and energy price increase) can be found in the supplementary information sections at the end of Chapters 2 and 6.

1.4 Thesis Objective and Outline

The main objective of this thesis is to contribute to the understanding of the interrelation between enacted policies in the coming one or two decades and long-term climate targets. This includes both the ‘diagnostic’ analysis of the impact of announced sub-optimal policy stringency and the ‘explorative’ analysis of different policy options to reconcile long-term ambition and short-term political realities.

The first part of this thesis, Chapters 2 to 4, provides a comprehensive analysis of the consequences of a policy delay for the achievability of stringent climate targets like the 2 °C target. The analysis extends the notion of the emissions gap and identifies impacts of a delay that are more relevant for society and policy-makers than mere excess emissions. Both the impacts on different cost metrics relevant for a socio-economic evaluation (including proxies for distributional impacts, see Section 1.3.5) as well as the underlying energy system impacts are relevant for such an analysis. The former analysis strives to answer how much a delay of policies impacts each of the different indicators, whereas the latter analysis asks which lock-ins and path dependencies in the energy system are the cause for cost increases and thus have to be avoided to mitigate the cost increases due to delay.

The answer to this question is the basis for the second part of the thesis, Chapters 5 and 6. The objective here is to analyze to what extent targeted second-best policy portfolios can compensate for the lack of optimal policies, thus providing a bridge to keeping stringent climate targets achievable at manageable costs. More specifically, the role of energy consumer subsidies, low-carbon support policies and policies regulating carbon-intensive technologies are analyzed, together with their interplay with two possible sub-optimal carbon pricing policies, a carbon tax and a cap-and-trade scheme. The objective here is to go beyond the trivial policy message that it is optimal to start comprehensive policies as early as possible and to explore the potential impact of second-best policy packages that seem easier to be implemented than the first-best policy of an optimally high comprehensive carbon price.

The following list summarizes the main research questions. The ensuing remainder of the section details how they are addressed in the individual chapters.

- What is the trade-off between climate target stringency and mitigation cost?
- How is this trade-off influenced by timing of policies and technology availability?
- Which cost metrics are relevant?
- What are the implications in terms of cost and feasibility of a delay of climate policies consistent with the 2 °C target?
- What are the energy system implications of a delay of climate policies?
• How do the energy system dynamics in delayed action scenarios differ across a wide range of EEMs?
• What are the key uncertainties regarding the impact of a delay?
• What are the short- and long-term impacts of a removal of energy consumer subsidies on emissions, regional welfare, and deployment of low-carbon technologies?
• What is the interrelation between a removal of energy consumer subsidies and climate policies?
• How do carbon pricing and technology policies interact in a scenario with moderate near-term climate policy stringency?
• What are the specific effects of technology policies that regulate high-carbon technologies and such that support low-carbon alternatives? How do they interact?
• What is the comparative advantage of alternative approaches for implementing carbon pricing, i.e. a carbon tax vs. cap-and-trade?
• How much can a sub-optimal policy mix contribute to keeping ambitious targets within reach at manageable costs?

1.4.1 Structure of the Thesis

The research conducted to answer these questions is presented in the form of five articles reproduced here as Chapters 2 to 6. The author of this thesis contributed significantly to all of these articles (see the statement of contribution on page 193), which are all published in peer-reviewed scientific journals. Each article answers specific research questions in a self-contained manner (see below). Taken together, they give a comprehensive perspective on the research objective of this thesis as described above.

Figure 4 illustrates the line of argument underlying the sequence of chapters on the horizontal axis. In addition, the vertical axis indicates whether the study is based on analysis by a single or multiple models. While all studies employ the REMIND model, Chapters 3 to 5 compare results from REMIND with those from other models. The comparative advantage of single-model papers is that the scenario set-up can be more elaborate and many iterations of scenario exploration and modification can be done. This way, the main argument of the papers can be made most transparent through the tailor-made scenario design. Multi-model studies in turn allow for testing which results are robust across various models with different structural and parametric assumptions and where results differ. Chapters 3 and 4 are based on model-intercomparison projects. In these projects, the different modeling teams followed harmonized scenario protocols so that the results across models are directly comparable. The comparisons in Chapter 5 are based on previously published scenarios so that scenario definitions are not fully equivalent.

To close this introductory chapter, a short presentation of each of the five individual research chapters follows. Chapter 7 at the end of this thesis contains a concluding discussion of results as well as a summary of limitations and options for future research.
Chapter 2: Economic mitigation challenges: how further delay closes the door for achieving climate targets

This chapter sets the scene by giving a comprehensive analysis of the trade-off between target stringency and socio-economic challenges as measured by four different economic cost metrics. It is based on 285 runs of the REMIND model, such that the impact of technology availability and the impact of the timing of climate policies (starting after 2010, 2015, 2020 or 2030) can be analyzed in detail.

Chapter 3: Implications of weak near-term climate policies on long-term mitigation pathways

Prepared in the context of the RoSE model intercomparison exercise, this paper analyzes the impact of regionally fragmented moderate climate policies in the three EEMs GCAM, REMIND and WITCH, as well as the adoption of a stringent climate target after following the moderate trajectory until 2020 or 2030. Both socio-economic costs as well as the overall energy system transformations in terms of final energy demand and decarbonization of energy provision are analyzed.
Chapter 4: Carbon lock-in through capital stock inertia associated with weak near-term climate policies

Forming part of the AMPERE model intercomparison project, this chapter explores the implications of a delay of stringent climate policies until 2030 using nine EEMs. Complementing two companion papers on overall impacts on costs and the role of technology availability (Riahi et al., 2015) and energy technology up-scaling (Eom et al., 2015), the focus here is on the allocation of the allowable emissions budget across time and technologies. The aim of the analysis is to identify robust features as well as differences across models with respect to emission shares and dynamics. Additionally the impact of assuming lower future energy demand is analyzed in detail.

Chapter 5: Long-term climate policy implications of phasing out fossil fuel subsidies

The role of phasing out fossil fuel subsidies for consumers is analyzed using scenarios from REMIND and comparing them to literature using the ENV-linkages (Burniaux and Chateau, 2010) and World Energy Model (IEA, 2012). We consider different phase-out schemes based on recent policy proposals in scenarios with or without additional climate policies. We analyze the impacts on emissions, welfare distribution and technology deployment with regional detail.

Chapter 6: Complementing carbon prices with technology policies to keep climate targets within reach

We analyze different second-best policy packages until 2030, combining two pricing instruments with three technology policy packages. By continuing all scenarios with optimal policies to reach 2 °C after 2030 we can extract both the mid-term and long-term economic challenges associated with reaching this target and can compare the second-best policies with the benchmark starting with optimal policies immediately. The scenario design allows for the quantification of the individual effects of each policy as well as the interactions between them. Furthermore, by considering four different economic indicators, we can work out the trade-offs that exist between using different policy instruments.

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Chapter 2

Economic Mitigation Challenges: How Further Delay Closes the Door for Achieving Climate Targets*

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Economic mitigation challenges: how further delay closes the door for achieving climate targets

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Abstract
While the international community aims to limit global warming to below 2 °C to prevent dangerous climate change, little progress has been made towards a global climate agreement to implement the emissions reductions required to reach this target. We use an integrated energy–economy–climate modeling system to examine how a further delay of cooperative action and technology availability affect climate mitigation challenges. With comprehensive emissions reductions starting after 2015 and full technology availability we estimate that maximum 21st century warming may still be limited below 2 °C with a likely probability and at moderate economic impacts. Achievable temperature targets rise by up to ~0.4 °C if the implementation of comprehensive climate policies is delayed by another 15 years, chiefly because of transitional economic impacts. If carbon capture and storage (CCS) is unavailable, the lower limit of achievable targets rises by up to ~0.3 °C. Our results show that progress in international climate negotiations within this decade is imperative to keep the 2 °C target within reach.

Keywords: climate change mitigation, 2 °C target, delayed climate policy, low-carbon technologies

Online supplementary data available from stacks.iop.org/ERL/8/034033/mmedia

1. Introduction

Climate change is a major global challenge (IPCC 2007). The ultimate goal stated in the United Nations Framework Convention on Climate Change is to ‘prevent dangerous anthropogenic interference with the climate system’ (UNFCCC 1992). The international community adopted the long-term target of limiting the increase of global mean temperature to no more than 2 °C relative to pre-industrial levels. However, progress in the implementation of concrete emissions reduction policies has been slow. Even with the implementation of climate policy measures in several world regions, global emissions have continued to rise (Peters et al 2013, JRC/PBL 2012). Reaching the 2 °C target with high likelihood implies a tight limit on cumulative future anthropogenic greenhouse gas (GHG) emissions (Meinshausen et al 2009). Various reports have concluded that pledged national 2020 reduction targets fall short of the reductions required to meet the 2 °C target in a cost-optimal way (Höhne et al 2012, Rogelj et al 2010).
The decarbonization of economies requires a massive transformation in the way energy is produced and used (Fisher et al. 2007, GEA 2012). Currently, the deployment of many low-carbon technologies faces technological difficulties or limited political support. For instance, carbon capture and storage (CCS), large-scale bioenergy production and nuclear energy are subject to sustainability concerns and public opposition. Similarly, integrating major shares of wind and solar power is challenging because of fluctuating supply from these sources.

In the past most climate mitigation scenarios were prepared under the idealistic assumptions of full flexibility in technology choice, globally coordinated climate policies ensuring that emission abatement would occur where it is cheapest, and the immediate start of climate policies (Fisher et al. 2007, Knopf et al. 2011). Meanwhile, several studies have considered climate mitigation scenarios with restricted technology portfolios (Edenhofer et al. 2010, Azar et al. 2010, Tavoni et al. 2012), while others have investigated climate stabilization after a period of fragmented and delayed climate policy (Clarke et al. 2009, Luderer et al. 2012a, Jakob et al. 2012, van Vliet et al. 2012, IEA 2009). These studies showed that both technology availability and fragmented climate policy have a strong effect on the cost and achievability of climate targets. Only a few studies have analyzed the combined effects of delayed action and technology failure (Rogelj et al. 2013a, 2013b, van Vliet et al. 2012).

This study fills crucial research gaps. Currently available studies have almost exclusively used inter-temporally aggregated mitigation costs and carbon prices as indicators of mitigation effort. However, policymakers are much more concerned about the shorter term effects and distributional impacts of mitigation policies. Our work quantifies the trade-offs between the stringency of long-term climate targets on the one hand, and policy-relevant socio-economic challenges such as transitory costs, short-term energy price increases, and the potential redistribution of wealth induced by a global cap-and-trade regime on the other. By analyzing the impact of climate policy frameworks on these economic mitigation challenges, we examine how a further delay of global action forecloses long-term stabilization levels and technology choices.

2. Methods

We used the integrated energy–economy–climate model REMIND to produce a large ensemble of 285 scenario experiments, which combine different assumptions on (a) technology availability, (b) the start date of comprehensive global climate policies, and (c) globally harmonized carbon price levels.

2.1. Modeling framework

REMIND is an inter-temporal general equilibrium model of the macro-economy with a technology-rich representation of the energy system (Leimbach et al. 2009, Bauer et al. 2012, Luderer et al. 2012b). It represents capacity stocks of more than 50 conventional and low-carbon energy conversion technologies, including technologies for generating negative emissions by combining bioenergy use with carbon capture and storage (BECCS). REMIND accounts for relevant path-dependencies, such as the build-up of long-lived capital stocks, as well as learning-by-doing effects and inertias in the up-scaling in innovative technologies. These path-dependencies are of particular importance for the study of energy transformation pathways in general and delayed action scenarios like the ones considered here in particular. REMIND represents 11 world regions, and operates in time-steps of five years in 2005–2060, and ten years for the rest of the century.

To examine the carbon cycle and climate system response to emissions, we employ a probabilistic setup of the reduced complexity climate model MAGICC (Wigley and Raper 2001, Meinshausen et al. 2009, 2011). A detailed description of the modeling framework is available in the supplementary information (SI) section 1 (available at stacks.iop.org/ERL/8/034033/mmedia).

There are important caveats to the use of an economic model for the analysis of global, long-term mitigation pathways. For instance, the societal choices and behavioral patterns that drive energy supply and demand can be, unlike physical laws, subject to change and are therefore inherently difficult to predict (Koomey 2002). Similarly, the development and performance of energy supply technologies is highly uncertain. Our analysis should therefore not be mistaken for a prediction of future developments, but rather a strategic exploration of climate policy options based on a set of mitigation scenarios. As described in section 2.2, we use a large number of scenarios with different technology and policy assumptions to cover a wide spectrum of plausible climate futures.

2.2. Scenario definition

Along the policy-timing dimension, we consider three scenarios Frag2015, Frag2020 and Frag2030 with delayed adoption of cooperative mitigation action with globally harmonized GHG pricing resulting in comprehensive emissions reductions, assuming that climate policies remain weak and fragmented until 2015, 2020 and 2030 (cf figure 3(a)), respectively. In the time-steps before the start of cooperative action, world regions are assumed to follow a weak, fragmented climate policy regime based on a weak interpretation of the pledges or reduction proposals under the Cancun Agreements or Copenhagen Accord for 2020, and an extrapolation of the implied climate policy ambition beyond 2020 (WeakPol reference scenario, see SI section 6 (available at stacks.iop.org/ERL/8/034033/mmedia) and Luderer et al. 2013). The WeakPol scenario yields similar global emissions by 2020 as the full implementation of the unconditional pledges under lenient accounting rules (UNEP 2012). While Frag2015 marks an optimistic possible outcome of the current climate negotiations with a 2015 climate agreement resulting in enhanced reductions in 2020, Frag2030 is a possible outcome of a failure of the current round of climate negotiations, with a continuation of weak and fragmented climate policies until 2030. In addition, we consider a
Along the scenario dimension of technology availability, we consider seven alternative cases, similar to those used in Kriegler et al. (2013): (i) default—full technology portfolio, (ii) NoCCS—unavailability of CCS, (iii) NoBECCS—unavailability of CCS in combination with bioenergy (BECCS), (iv) LimBio—reduced bioenergy potential (100 EJ compared to 300 EJ in all other cases), (v) NucPO—phase out of investments into nuclear energy, (vi) LimSW—penetration of solar and wind power limited to 20%, and (vii) LowEI—lower energy intensity, with final energy demand per economic output decreasing faster than historically observed.

For each combination of technology and climate policy assumptions, we ran ten scenarios covering a wide spectrum of globally harmonized CO2 price levels adopted after the start of comprehensive climate policies5. Globally harmonized CO2 prices increase at 5% p.a., resulting in near cost-optimal inter-temporal emissions reductions to achieve a given long-term climate target (see SI section 5 for a discussion of the sensitivity of results to climate policy formulation available at stacks.iop.org/ERL/8/034033/mmedia). These scenarios yield a wide range of responses in the economy and the climate system. In addition, we performed some scenario experiments with a prescribed cumulative 2010–2100 GHG budget. They allow contrasting results from different scenarios with comparable climate outcomes. A more detailed description of the scenario setup is provided in SI section 2 (available at stacks.iop.org/ERL/8/034033/mmedia).

2.3. Economic indicators of mitigation challenge

We use four economic indicators to capture the breadth of economic and institutional challenges of stringent climate policies, and their dependence on the timing of climate policies and technology availability. (i) Aggregated mitigation costs are a commonly used proxy indicator of the long-term effects of climate policies. We define them here as macro-economic consumption losses aggregated with a discount rate of 5% over the time horizon 2010–2100, relative to aggregated and discounted gross world product (GWP). In addition, we use (ii) transitional growth reduction, defined as the maximum reduction of decadal consumption growth induced by climate policies in percentage points (pp) as a proxy of potential short-term disruptions during the phase-in of climate policies; (iii) carbon market value, defined as the aggregated and discounted value of greenhouse gases emitted from 2010–2100, as a proxy for the potential distributional conflicts when defining the regional and sectoral burden sharing under a comprehensive cap-and-trade regime; and (iv) the short-term energy price increase induced by climate policies, measured in terms of an aggregated global final energy price index, as a proxy for the effect of climate policies on the energy bills of households and firms. These indicators allow us to assess not only the long-term mitigation challenges, but also the challenges encountered at time-scales that are more relevant for today’s decision-makers. SI section 3 (available at stacks.iop.org/ERL/8/034033/mmedia) provides the technical details on these indicators, and the rationale behind the parameter ranges chosen. Note that these economic indicators only measure efforts related to emissions reductions, but do not account for avoided damages or co-benefits of climate change mitigation.

3. Results

3.1. Temperature-cost-trade-off curves

Relating mitigation to maximal temperature increase until 2100 establishes temperature-cost-trade-off curves, as shown in figure 1. The lower the maximal temperature over the 21st century, the higher the inter-temporally aggregated mitigation costs as a share of GWP. This property gives rise to the notion of an economic achievability frontier, i.e., a lower limit of achievable climate targets for a given macro-economic cost level. The temperature-cost-trade-off curves are highly convex, i.e., costs increase disproportionally with the increasing stringency of the long-term temperature target.

The climate system’s response to anthropogenic emissions is subject to substantial uncertainties, which we address explicitly. In the Frag2015 scenario with default technology assumptions, limiting global warming to below 2°C with a 50% likelihood (ΔT50) results in long-term mitigation costs of around 1.0% of GWP. Reaching the target with a likelihood of two-thirds (ΔT67) implies long-term costs of 1.4%. We find a very tight, approximately linear relationship ΔT50 = 0.901ΔT67 + 0.021°C (cf figure S5 available at stacks.iop.org/ERL/8/034033/mmedia), based on which these two confidence levels can be easily converted into each other.

5 CO2 prices exhibit strong regional differences in the Frag2015, Frag2020 and Frag2030 scenarios until 2015, 2020 and 2030 respectively, and converge to the globally harmonized level thereafter.
Figure 2. Temperature-cost-trade-off curves showing the effect of timing of global comprehensive mitigation action on (a) aggregated mitigation costs, (b) transitional consumption growth reductions, (c) carbon market value, and (d) energy price increase (default technology assumptions). X-axis shows temperature targets (maximum 2010–2100 temperatures) reached with a 67% likelihood. Bar charts indicate economic challenge of limiting warming to 2 °C.

Figure 3. (a) Emission pathways and (b) consumptions losses for the reference scenario with weak polices (WeakPol), as well as for stabilization scenarios with a cumulative emissions budget of 2500 GtCO₂e, with immediate (immediate) or delayed implementation of comprehensive emissions reductions (Frag2015, Frag2020, Frag2030).

In the remainder of this letter, temperature targets refer to levels achieved with 67% likelihood.

3.2. Effect of delayed action

For all economic mitigation challenge indicators, a further deferral of comprehensive global emissions reductions results in a shift of the temperature-cost-trade-off curves towards higher costs and higher temperatures (figure 2). Thus, a delay of comprehensive climate policies implies not only higher costs for reaching a given climate target (bar charts), but also an increase of the lower level of climate targets achievable within the range of acceptable cost levels, as indicated by the arrows in the figure. For climate targets around 2 °C, the effects of delay on inter-temporally aggregated costs are substantial. This is in spite of the fact that lower costs in the short-term partially offset the higher long-term costs, which are subject to greater discounting (figure 3(b)).

Since mitigation costs as a share of GWP increase over time, aggregated mitigation costs depend on the discount rate used for the inter-temporal aggregation. The sensitivity studies shown in SI section 4 (available at stacks.iop.org/ERL/8/034033/mmedia) demonstrate that lower discount rates result in higher mitigation costs and stronger effects of delayed action, but do not change the qualitative conclusions of the analysis.
The longer the climate policy regime remains weak and fragmented, the higher are the emissions reduction rates required after the implementation of comprehensive climate policies to reach low stabilization targets (figure 3(a), see also Stocker 2012). This is mirrored in the development of policy costs measured in terms of consumption losses over time, which show an abrupt increase of costs in case of cooperative action delayed beyond 2030 (figure 3(b)). The effect of delay on the transitional growth reduction after implementation of comprehensive emissions reductions is therefore even more pronounced than the effect on aggregated mitigation costs. For aggregated mitigation costs in the range of 2–4% of GWP, lowest achievable climate targets in Frag2030 exceed those found for Frag2015 by 0.2–0.3 °C. For transitional mitigation costs in the range of 2.5–5 pp, the shift even amounts to ~0.4 °C. Recent macro-economic data suggest that a short-term growth reduction of 5 pp is comparable to the effect of the financial crisis (IMF 2012). We also find that transitional costs for limiting warming to 2 °C are three times higher in case of Frag2030 than in Frag2015.

The impact of mitigation timing on short-term energy price increases is similar to that on the transitional growth reductions. Lowest climate targets achievable at energy price increases of 50–100 pp shift by almost 0.4 °C if climate policies remain weak and fragmented until 2030 (figure 2(d)). Increases of final energy prices in comparable magnitude have been observed in the past for individual regions or energy carriers (see SI section 3 available at stacks.iop.org/ERL/8/034033/mmedia). In case of full technology availability, the short-term energy price increase induced by climate policies consistent with 2 °C stabilization remains moderate at around 25 pp even in the Frag2030 scenario, but more than thrice this value in Frag2030.

Carbon pricing—which ensures economic efficiency (Fisher et al. 1996)—emerges as a crucial institutional challenge. If the 2 °C target is implemented in the Frag2015 scenario, the cumulated present value of emissions permits in 2010–2100 amounts to US$ ~50 trillion, which is comparable to the market value of crude oil consumed over the same period in the baseline scenario without climate policy. If action is delayed beyond 2030, the carbon market value implied by 2 °C stabilization more than doubles, and lowest climate targets achievable at cumulated carbon market values of US$ 50–100 trillion shift by ~0.3 °C.

3.3. Effect of technology availability

We focus the further discussion on aggregated mitigation costs and transitional growth reduction (figures 4 and 5). Insights for carbon market value and energy price increases are qualitatively similar and shown in figures S2 and S7 (available at stacks.iop.org/ERL/8/034033/mmedia). We observe that the availability of CCS technologies has a strong influence on target achievability. Lowest achievable mitigation targets increase by 0.2–0.3 °C if CCS cannot be used. Limited bioenergy potential also results in a significant shift in the temperature-cost-trade-off curves. The similarity of the results of (a) unavailability of BECCS and (b) unavailability of both BECCS and fossil CCS underscores the importance of negative emissions, and suggests that BECCS is more crucial for low stabilization than fossil CCS. A variety of alternative low-carbon options for electricity production is available; therefore, limitations on nuclear or wind and solar power have relatively small economic effects. By contrast, if economies increase their energy efficiency at a higher rate than has been historically observed, costs for reaching the 2 °C target decrease by 40%, and even lower climate targets become achievable already at moderate costs.

3.4. Targets achieved with temporary temperature overshoot

So far, we focused on climate outcomes in terms of maximal temperature increases over the 21st century. This is equivalent to formulating climate targets as not-to-exceed. Alternatively, 2100 temperature levels can be considered, equivalent to allowing for temporary overshooting of the long-term climate target. For the high end of mitigation cost levels, and if biomass and CCS are available, we observe that in terms
Figure 5. Overview of the combined effects of mitigation timing and technology availability on achievability of either not-to-exceed targets (in terms of maximum 2010–2100 temperature increase, upper panels), or 2100 temperature targets that allow for temporary overshoot (lower panels). Graphs show economic challenges (color shading) in terms of aggregated policy costs (left panels (a), (c)), and transitional growth reduction (right panels (b), (d)), as a function of temperature targets reached with 67% likelihood. Dark gray areas at the base of bars indicate temperature target levels that were not achieved with the range of carbon price paths assumed.

of 2100 temperatures considerably lower climate targets can become achievable than in terms of maximal 2000–2100 temperatures (figures 5 and S7, S8 available at stacks.iop.org/ERL/8/034033/mmedia). In the Frag2015 scenario with default technology assumptions, 2100 temperatures achievable with 67% likelihood at aggregated costs of 4% of GWP drop to 1.35 °C, compared to 1.6 °C in terms of maximum 2000–2100 temperatures. The results also show that technology availability has a greater influence on lowest achievable 2100 temperature levels than on maximum 21st century temperatures (figure S6 available at stacks.iop.org/ERL/8/034033/mmedia). This is because for trajectories with overshoot, the effects of technologies only come to bear in a limited time frame (until the maximum temperature is reached), while in case of 2100 temperatures the effects of technology cumulate over the entire century. This is particularly relevant for bioenergy and CCS, which are ramped up relatively slowly in the 1st half of the century, but become very significant after 2050, if the technologies are available.

4. Discussion and conclusions

In view of the slow progress of international climate negotiations and emissions reduction efforts, the political achievability, and the technological and economic implications of limiting global warming to 2 °C are debated controversially. Model-based scenarios of climate change mitigation pathways are crucial tools for assessing the implications of alternative policy choices. Our work maps out the trade-offs between the stringency of climate targets and economic mitigation challenges at a very high level of detail. It shows how a continuation of ineffective climate policies reduces the option space for future climate policy, increasing mitigation challenges and the reliance on technologies for removing CO₂ from the atmosphere.

Under optimistic assumptions about the outcome of current climate negotiations and technology availability, we estimate that economic mitigation challenges become prohibitively high for temperature stabilization targets below ~1.7 °C. This means that much of the room to accommodate the 2 °C target has already been consumed. The results suggest that delaying comprehensive emission reductions by
Another 15 years pushes this target out of reach. In case of technology limitations, the urgency of reaching a global climate agreement is even higher.

A continuation of weak climate policies inevitably increases the risk of exceeding the 2°C threshold. Returning to 2°C in such a scenario will be difficult, and requires large-scale deployment of BECCS. We find that temperature levels reached in 2100 depend to a much higher extent than maximum 2010–2100 temperatures on the availability of technologies, with unavailability of CCS reducing achievable target levels by almost 0.5°C.

Our research also demonstrates that the effects on short-term consumption growth and energy prices as well as the redistribution of wealth induced by CO2 pricing are crucial challenges of mitigation pathways consistent with 2°C. This finding points to potentially strong distributional effects of climate policies, which increase strongly if comprehensive climate policies are delayed further. Additional work is needed to analyze policy instruments and institutional requirements to address these challenges.

The results have important implications for climate policy. They show clear trade-offs between long-term climate targets and economic mitigation challenges. They also demonstrate that these trade-offs depend strongly on the start date of substantial emissions reductions and technology availability. The longer the international community delays the implementation of comprehensive climate policies, the more critical these trade-offs will be.

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Supplementary Information:

Economic mitigation challenges: how further delay closes the door for achieving climate targets

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1 Methods

Our analysis combines a state-of-the-art integrated energy-economy-climate model (REMIND) with the probabilistic reduced-form climate model MAGICC. The following sections provide an overview of these modeling frameworks.

1.1 The integrated energy-economy-climate model REMIND

We use version 1.5 of the energy-economy-climate model REMIND to derive greenhouse gas (GHG) emission pathways and policy cost estimates for a large ensemble of mitigation scenarios with different assumptions on technology availability, timing of cooperative action, and carbon price levels under a global cooperative climate policy regime.

A detailed description of REMIND 1.5 is available from (Luderer et al 2013b). REMIND is a global model of the energy-economy-climate system spanning the period 2005-2100, with 5-year time steps between 2005 and 2060, and ten year time steps thereafter. The macro-economic core of REMIND is a Ramsey-type intertemporal general equilibrium model in which global welfare is maximized, as found in similar form in other integrated assessment models such as RICE (Nordhaus and Yang 1996) or MERGE (Manne et al 1995). The model computes a unique Pareto-optimal solution which corresponds to the market equilibrium in the absence of non-internalized externalities. The world is divided into 11 regions: there are five individual countries (China, India, Japan, United States of America, and Russia) and six aggregated regions formed by the remaining countries (European Union, Latin America, Sub-Saharan Africa without South Africa, a combined Middle East / North Africa / Central Asia region, Other Asia, Rest of the World). Trade is explicitly represented for final goods, primary energy carriers, and, in case of climate policy, emission allowances. Macro-economic production factors are capital, labor, and final energy. The economic output is available for investments into the macro-economic capital stock as well as for consumption, trade of goods, and financing the energy system.

The macro-economic core and the energy system module are hard-linked via final energy demand and costs incurred by the energy system. Economic activity results in demand for final energy such as transport energy, electricity, and non-electric energy for stationary end-uses. This final energy demand is determined by a production function with constant elasticity of substitution (nested CES production function). The energy system module accounts for endowments of exhaustible primary energy resources (coal,
oil, gas and uranium) as well as renewable energy potentials (biomass, hydro power, wind power, solar energy, geothermal energy). REMIND represents capacity stocks of more than 50 technologies for the conversion of primary energy into secondary energy carriers as well as for the distribution of secondary energy carriers to end use sectors. In particular, the model accounts for the possibility of combining fossil fuel and bioenergy use with carbon capture and storage (CCS). Since trees and crops extract CO₂ from the atmosphere, deploying bioenergy in combination with CCS (BECCS) can result in net negative emissions. As shown by the results for technology-constrained scenarios, BECCS technologies are of crucial importance for the achievability of low stabilization targets. Learning-by-doing effects are explicitly represented via learning curves for wind and solar technologies as well as electric vehicles. REMIND does not have any hard limits on the expansion rate of new technologies. In order to mimic real-world inertias in technology up-scaling, a cost penalty ("adjustment costs") is applied that scales with the square of the relative change in capacity investments. This yields technology diffusion rates that are broadly in line with historical patterns (Wilson et al 2013). The retirement of fossil capacities before the end of their technological life-times is possible, but limited to a rate of 4% per year.

REMIND calculates energy related non-CO₂ GHG and aerosol emissions via time-dependent emission factors. Emissions from agriculture and land-use are obtained from the land-use model MAgPIE (Lotze-Campen et al 2008). Emission reduction potentials of non-energy related CO₂, CH₄ and N₂O emissions are represented via marginal abatement cost curves. Emissions of F-Gases are prescribed exogenously based on RCP data (van Vuuren et al 2011a).

REMIND has been used for numerous analyses of the economics of climate change mitigation (Leimbach et al 2010a, 2010b, Bauer et al 2012a, Lueken et al 2011, Bauer et al 2012b, Luderer et al 2012c). REMIND has also participated in a number of past model inter-comparison exercises (Edenhofer et al 2010, Luderer et al 2012a, Calvin et al 2012), and is currently involved in several on-going inter-comparison exercises.

1.2 The probabilistic climate model MAGICC

To represent uncertainties in the carbon cycle and climate system response to emissions, we employ the reduced complexity climate model MAGICC (version 6) (Wigley and Raper 2001, Meinshausen et al 2011c, 2011a). Here, we employ a probabilistic setup of the model. The parameter space has been constrained by historical
observations of ocean heat uptake (Domingues et al 2008) and surface temperatures over land and ocean in both hemispheres (Brohan et al 2006), using a Metropolis Hastings Markov Chain Monte Carlo approach as described in (Meinshausen et al 2009). A 600-member ensemble of the resulting joint distribution of the 82-dimensional parameters space has then been drawn, so that the marginal climate sensitivity distribution closely represents the IPCC Fourth Assessment Report conclusions in regard to our uncertainty on climate sensitivity (Rogelj et al 2012). Differently to the setup in (Meinshausen et al 2009, Rogelj et al 2012), we include a probabilistic permafrost module (Schneider von Deimling et al 2012)—thereby accounting for the effect of potential climate feedback from permafrost by additional release of carbon dioxide and methane release from the upper soil compartment. The omission of the permafrost feedback effect has previously been regarded as a research gap (Hatfield-Dodds 2013), although we note that the temperature effect until 2100 is limited.

We consider all important greenhouse gases, tropospheric ozone precursors, the direct and indirect aerosol effects and landuse albedo. CO₂, CH₄, N₂O, sulfur, black carbon and organic carbon emissions are endogenous results from the REMIND model, while other forcing components are complemented from corresponding RCP emission scenarios (van Vuuren et al 2011a, 2011b, Masui et al 2011). For emissions of ozone depleting substances we assume the WMO2006 emissions scenario – consistent with the setup for creating the RCP GHG concentration profiles (Meinshausen et al 2011b).

2 Scenario design

Our analysis is based on a large set of climate mitigation scenarios compiled along the dimensions of (i) timing of global cooperative mitigation action, (ii) availability of low carbon technologies, and (iii) stringency of long-term climate policies, controlled by different globally harmonized carbon price levels. The combination of these dimensions yields a scenario ensemble of 285 different REMIND runs, each representing one energy-economic development pathway. For each scenario, the GHG emission trajectories resulting from REMIND were used to calculate 600 climate realizations with the probabilistic climate model MAGICC, yielding a total of 171'000 climate model simulations. The variations along the different scenario dimensions are presented and motivated in the following.
2.1 Timing of climate policy

In the long-term, any climate stabilization target requires near-zero emission levels. As a consequence, climate policy will only be successful if it eventually establishes a comprehensive climate regime that covers virtually all countries and emitting sectors. The second scenario dimension explores delay in setting up such a global comprehensive climate policy regime. The specifications of the delayed-action scenarios follow those of the RoSE study (Luderer et al. 2013a).

**P0. Weak-policy baseline (WeakPol)**

This scenario is designed as a reference scenario that includes weak climate policies. It is meant to represent the unambitious end of short- and long-term climate policy developments. It was constructed by considering existing climate policies, a weak interpretation of the 2020 Copenhagen Pledges, and an extrapolation of these targets beyond 2020 based on emissions intensity (GHG emissions per unit of GDP). Three country groups are considered: industrialized countries (Group I), developing countries excluding resource exporters (Group II), and fossil resource exporters of the former Soviet Union and Middle East (Group III). Climate policy is assumed to remain fragmented, with no emissions trading between regions until 2020. Limited trading of emissions between industrialized and developing countries is allowed after 2020. It is assumed that resource-exporting countries (Group III) will not adopt any binding targets. Furthermore, it is assumed that land-use emissions will not be subject to carbon pricing. A detailed description of the WeakPol scenario is provided in Section SI 6. The assumptions of the WeakPol scenarios with regard to regional emission reduction targets are identical to those used in Luderer et al. (2013).

**P1. Weak and Fragmented climate policy until 2015 (Frag2015)**

The Frag2015 scenario considers the most optimistic possible outcome of the current climate negotiation process and the Durban Platform. It assumes that a global climate agreement is reached by 2015, and that comprehensive emission reductions are implemented from 2020 onwards. Until 2015, the model follows the weak policy scenario, without anticipating more stringent future climate policies. Starting with the 2020 model time step, a global cooperative climate regime is implemented with comprehensive regional and sectoral coverage.

**P2. Weak and Fragmented climate policy until 2020 (Frag2020)**

The Frag2020 scenario considers a somewhat more pessimistic outcome of the Durban Platform, assuming that it fails to deliver 2020 emission reductions beyond those of the
current pledges as implemented in the WeakPol scenario, and that the implementation of comprehensive global emissions reductions is delayed until 2025.

**P3. Weak and Fragmented climate policy until 2030 (Frag2030)**

The Frag2030 scenario assumes a failure of the Durban Platform negotiations, resulting in unambitious and fragmented climate policies following the WeakPol scenario without anticipating more stringent future climate policies until 2030. Comprehensive global emissions reductions start in 2035.

**P4. Immediate action (Immediate)**

In the immediate action scenario we assume that global cooperative climate mitigation policies start immediately, with global comprehensive emission reductions starting in the 2015 model time step. It must be considered hypothetical, since none of the current climate negotiation tracks would be able to deliver such an outcome.

### 2.2 Technology availability

Earlier studies (Azar et al 2010, Edenhofer et al 2010, Tavoni et al 2012) have shown the crucial importance of low-carbon technologies for costs and achievability of low stabilization targets. To further explore the influence of technology availability on the lower limit of achievable climate targets, we produced seven scenario sets with different idealized assumptions on technology availability. With the exception of the the NoBECCS case, the scenario specifications are identical to those used in the EMF27 study (Kriegler et al 2013):

**T1. Full technology portfolio (Default)**

All technologies represented in the REMIND model are assumed to be available. Default assumptions regarding final energy demand are implemented, with autonomous energy intensity improvements (AEII, i.e., reductions in final energy demand per unit of GDP in absence of climate policy) in line with the historical rate of about 1.2%/yr. Bioenergy use is limited to 300 EJ/yr.

**T2. No carbon capture and storage (NoCCS)**

All conversion technologies with carbon capture and storage, both with fossil fuels or bioenergy as feed-stocks, are excluded from the mitigation portfolio. This scenario setting is motivated by the slow progress in up-scaling CCS to commercial scale, potential environmental impacts and limited public acceptance of geological storage in some countries, as well as institutional barriers.
**T3. No bioenergy combined with carbon capture and storage (NoBECCS)**

All technologies that combine bioenergy use with carbon capture and storage are excluded from the mitigation portfolio. Specific challenges applying to BECCS in addition to those of CCS include (a) the lower technological maturity of BECCS technologies, (b) sustainability constraints to bioenergy production (see LowBio case), (c) institutional challenges related to incentivizing negative emissions.

**T4. Low bioenergy availability (LimBio)**

The global bioenergy potential is limited to 100 EJ. This scenario is motivated by a variety of concerns about the sustainability of large-scale bioenergy production regarding (a) scarcity of arable land, (b) potential freshwater demand for irrigation, (c) effect on food prices, (d) potential indirect land-use change emissions (ILUC) induced by bioenergy production, and (e) potential loss of biodiversity.

**T5. Nuclear phase-out (NucPO)**

No nuclear capacity additions beyond those currently under construction. This scenario is motivated by limited public acceptance of nuclear power in view of (a) security concerns in the aftermath of the Fukushima accident, (b) challenges related to nuclear waste disposal, and (c) proliferation concerns.

**T6. Limited Wind and Solar Power (LimSW)**

The share of electricity production from wind and solar power is limited to 20% of total electricity in each region. This scenario is motivated by the challenges related to the fluctuating supply from variable renewable energy sources.

**T7. Low energy intensity (LowEI)**

This set of scenarios assumes autonomous energy intensity improvements that are higher than those in the Default scenario, and exceed those observed historically. Baseline energy intensity is 25% lower than in Default in 2050, and 40% lower than in Default in 2100. The LowEI scenarios describe a world in which behavioral changes result in lower demand for final energy, and barriers for energy efficiency improvements are decreased.

2.3 **Carbon price levels**

We explore the effect of long-term climate policy stringency on climate stabilization levels and mitigation costs by varying the uniform carbon price signal applied in the global cooperative climate regime. We use 2020 reference carbon price levels of 5, 10,
20, 30, 40, 50, 100, 200 and 500 US$2005/tCO₂. Since the model's responsiveness to carbon pricing is highest at low to medium prices, we chose to use more narrowly spaced price steps below 50 US$2005/tCO₂. By default, we assume carbon prices to increase by 5% per year. This rate is very close to the model-endogenous discount rate, thus implying inter-temporal efficiency in minimizing cumulated GHG emissions. Section SI 4 explores the sensitivity of the results to the development of carbon prices over time.

We derived emission prices for non-CO₂ Kyoto gases based on global warming potentials from the IPCC AR4. We also calculate Baseline scenarios without any climate policies as a baseline for measuring the effect of mitigation.

3 Economic indicators of the mitigation challenge

For the analysis, we derived four indicators as proxies for the potential economic and political challenges associated with the implementation of climate policies: (i) aggregated mitigation costs as a measure for costs in the long run, (ii) transitional consumption growth reduction as a proxy of short-term economic effects, (iii) the aggregated carbon trade volume as a proxy for potential distributional conflicts under an international cap-and-trade system, and (iv) transitory energy price increases during the phase-in of comprehensive climate policies. They are defined and motivated in the following.

3.1 Aggregated mitigation costs (AMC)

Aggregate mitigation costs quantify the inter-intertemporally aggregated impact of climate mitigation policies on affluence. They are commonly used for characterizing long-term mitigation scenarios (B.S. Fisher et al 2007, Edenhofer et al 2010, Luderer et al 2012a). We calculate them as aggregated discounted consumption losses expressed relative to aggregated, discounted gross world product $GWP$ in the baseline:

$$ AMC = \left( \frac{\sum_{t=2010}^{2100} (C_{Baseline} - C_{Pol}) \cdot (1 + \delta)^{2010-t}}{\sum_{t=2010}^{2100} GWP_{Baseline} \cdot (1 + \delta)^{2010-t}} \right) \cdot 100\% $$

where $C$ denotes consumption, and a discount rate $\delta$ of 5% p.a. is used. While aggregated mitigation costs typically only amount to a few percent of cumulative economic output, they can be very significant in absolute terms. For the REMIND GWP baseline used here, each % of cumulative costs corresponds to discounted aggregated costs of US$ 19.6 tn in values of 2010. We use reference mitigation cost values of 2% and 4% of GWP for the
analysis of climate target achievability. This can be compared to the target to devote 0.7% of the gross national product (GNP) of OECD countries to Official Development Assistance (ODA) (United Nations 2002).

### 3.2 Transitional growth reduction (TGR)

Economic losses occurring during the transition from a regime without climate policy to a regime with stringent climate policies are a crucial barrier to the implementation of climate policies. We define the transitional growth reduction as the maximum of the difference between decadal consumption growth rate in the baseline and in the policy scenario, in units of percentage points [pp]:

\[
TGR = \max_{2010 < t < 2050} (g_{Baseline}(t) - g_{Pol}(t)),
\]

where for each scenario

\[
g(t) = \frac{(C(t + 5a) - C(t - 5a))}{C(t)} \cdot 100 \%
\]

is the decadal rate of consumption growth in units of %.

In the baseline, i.e., without climate policies, globally aggregated consumption grows at a rate of around 30-40 % per decade in the first half of the 21st century. The transition from a weak, fragmented climate policy regime to a regime with stringent and comprehensive emission reductions can slow consumption growth markedly. The timing of climate policy has important implications for the incidence of mitigation costs over time (see Figure 3 in the main paper). In case of immediate action, costs for reaching the 2°C target with a high likelihood are well below 1% of gross world product (GWP) in 2020 and increase gradually over time. For the scenarios with delayed cooperative action, the picture looks different: As the weak policies only have a small effect on the economy, near-term costs in the delayed scenarios with delayed cooperative action are rather small. Once a stringent global climate regime is implemented, however, costs increase to levels that exceed those in the immediate scenario reaching the same long-term target.

In some extreme scenarios, the transition from the weak, fragmented climate policy regime to stringent climate policies can therefore result in transitory mitigation costs of 10pp or higher. Such dramatic short-term effects render the political feasibility of such pathways questionable. For comparison, based on the IMF data (IMF 2012) the financial crisis of 2008 can be estimated to have reduced global economic output by around 5%.
Another study estimated the effect on the economies of the US and Europe to be of similar magnitude (Gros and Alcidi 2010). For the purpose of this study, we use a reference range of 2.5-5 pp to examine how climate policy induced consumption growth reductions limit economically achievable climate targets.

3.3 Energy price increases (EPX)

Energy price increases are among the most direct impacts of climate policies on households and firms. The impact of high energy prices will depend on the rates of price increases: if energy prices rise quickly, there is little time for adaptation through technological or behavioral changes.

To examine the effect of climate policies on energy prices, we derive a global final energy price index recursively, by calculating the market value of the final energy demand basket at time $t$ relative to the price the same final energy basket would have cost one period, i.e., 5 years, earlier:

$$EPX(t) = EPX(t - 5a) \cdot \sum_r \sum_i p_{i,r}(t) FE_{i,r}(t) / \sum_r \sum_i p_{i,r}(t - 5a) FE_{i,r}(t)$$

where $p_{i,r}, FE_{i,r}$ are the demands and prices of final energy carrier $i$ in region $r$, respectively, and $EPX(2010)$ is set to unity for normalization. This method is akin to the calculation of a chained consumer price index. The decadal growth rate of the energy price index can be readily calculated as

$$g_{EPX}(t) = (EPX(t + 5a) - EPX(t - 5a)) / EPX(t) \cdot 100\%$$

The maximum climate-policy-induced short-term energy price increase, in units of percentage points [pp] follows as

$$EPI = \max_{2010 < t < 2050} \left(g_{EPX,BaU}(t) - g_{EPX,Pol}(t)\right).$$

Figure S1a shows the development of the global energy price index over time. Energy prices would increase by a rate of roughly 20% per decade even if no climate policies were implemented, reflecting increasing global energy demand and a gradual depletion of fossil resources. Climate policy adds to this. In the Frag2015 scenario and under Default technology assumptions, reaching the 2°C target implies a maximum additional energy price increase of around 20 pp in the decade following the implementation of the
mitigation target. A further delay of a cooperative agreement results in much stronger short-term price increases of up to 100 pp in *Frag2030* (Figure 2d in the main paper).

Recently, substantial price increases have occurred in various industrialized countries, such as a 60% price increase in household electricity prices in Germany between 2000 and 2010, or a more than 100% price increase for gasoline in the US between 1998 and 2008 (ENERDATA 2013). For developing countries, there is some evidence that increases in energy prices can be causes of social unrest (Morgan 2008). For instance, a 70% increase of gasoline prices and a trebling of electricity prices (albeit in a much shorter time frame than a decade) were an important trigger for riots that occurred in Indonesia in 2008 (Purdey 2006). This leads us to assume that critical levels of transitional, climate-policy-induced energy price increases might be in the range of 50-100 pp.

### 3.4 Carbon market value (CMV)

Not only aggregated costs, but also distributional effects of climate policy matter. In order for climate policies to be efficient, carbon prices need to be harmonized across regions and sectors, so as to ensure equal mitigation costs at the margin (Stern 2007). While carbon pricing results in costs for emitters, it also produces potentially large revenues, for instance for the government in case of a carbon tax or full auctioning of emission permits in the context of an emissions trading scheme. Similarly, in the context of an international emissions trading scheme, the allocation of the permissible emissions budget across individual countries determines capital flows induced by emissions trading, and therefore has strong distributional implications (Lueken *et al* 2011, Luderer *et al* 2012b). We therefore use the cumulated carbon market value as an indicator of the institutional challenges to manage distributional conflicts arising from emissions trading both on the national and international level, and define it as

\[
CMV = \sum_{t=2010}^{2100} p_{CO2}(t) \cdot E(t) \cdot (1 + \delta)^{2010-t}
\]

where \(E\) refers to all positive greenhouse gas emissions, but excludes negative emissions from BECCS, and \(p_{CO2}(t)\) is the price of CO\(_2\).

The carbon market value as a function of temperature levels is quite sensitive to timing of mitigation action and technology availability. In the *Frag2015* scenario, reaching the 2°C target with a cap-and-trade regime that covers all regions and sectors implies an
aggregated carbon market value of about US$ 56 tn in values of 2010 (Figure 2c). The aggregated market value of fossil fuels consumed in a baseline scenario without climate policy is similar in magnitude, with oil accounting for US$ 46 tn, and coal, oil and gas combined for US$ 83 tn in values of 2010. We therefore assume that critical levels for the inter-temporally aggregated carbon market value might be in the range of US$2010 50-100 tn.

4 Sensitivity of aggregated mitigation costs to the discount rate

Since mitigation costs as a share of GWP are not constant over time (Figure 3b of the main paper), aggregated mitigation depend indeed on the discount rate used for the inter-temporal aggregation. To ensure consistency with the investment dynamics of the model, a discount rate of 5% p.a. was used for the calculation of the aggregated mitigation costs, which is in good agreement with the interest rate that emerges endogenously in the model (and historically observed rates of return on equity, see (Gollier 2012)). From the perspective of a representative household, the discount rate depends on two other ethical parameters, rate of pure time preference and the elasticity of marginal utility (Ramsey 1928). Alternative choices of these parameters can result in either lower or higher social discount rates. In the aftermath of the Stern Review (Stern 2007), a fierce debate about the appropriate use of discount rates in the economics of climate change emerged (Nordhaus 2007, Mendelsohn et al 2008, Weitzman 2007, Dasgupta 2006, Dietz and Stern 2008). Figure S4 shows a sensitivity study of aggregated mitigation costs for discount rates of 2.5%, 5% and 7.5% p.a. We find that a lower discount rate results in a higher aggregated costs indicator (since it puts more weight to the long-term costs, which are higher as a share of GWP) and a stronger economic penalties of delayed action.

5 Sensitivity of the results to the implementation of climate policies

We implemented long-term mitigation policies in terms of exponentially increasing carbon price pathways (cf. Section SI 2). In principle, other approaches are conceivable for representing climate policies in the model. Here we show that the approach taken represents close-to-optimal climate policies, and therefore allows us to explore the efficient frontier in the trade-off between climate targets and economic costs. The optimal pricing over time of the limited remaining atmospheric carbon budget implied
by a given climate target (Meinshausen et al 2009, Matthews et al 2009) is directly related to the economics of exhaustible resources, and is therefore akin to the optimal pricing of coal, oil and gas. Therefore, the Hotelling-rule (Hotelling 1931) can be applied. According to this rule, an inter-temporally optimal abatement strategy implies that carbon prices increases at the discount rate, in order to fulfill the intertemporal arbitrage condition determining the optimal use of the imposed carbon budget over time. The rate of increase of 5% p.a. that we assumed in our policy scenarios is close to the discount rate that emerges endogenously in REMIND, which is around 5-6 p.a. Therefore, a scenario experiment with an inter-temporal GHG emissions budget yields results that are very similar to those obtained from carbon price scenarios with comparable stringency (Figure S4).

There is no perfect correlation between the GHG emission budget and maximal 21st century temperature increases, especially in the case of delayed action scenarios with overshooting temperatures. We therefore explore the effect of implementing climate policy in terms of explicit not-to-exceed temperature targets. This allows the model to exploit flexibilities in adjusting the development of price ratios between long-lived and short-lived greenhouse gases over time and across different greenhouse gases (Manne and Richels 2001). We observe that the resulting aggregated mitigation costs implied by a certain maximum 21st century temperature are only marginally below the achievability frontier derived based on exponentially increasing carbon prices with global warming potentials (Figure S4a). On the other hand, the implementation in terms of explicit not-to-exceed temperature targets results in significantly higher costs as a function of 2100 temperature levels for temperature targets lower than 2°C. The reason for this is that a stringent GHG tax/budget scenario leads to temperature overshooting in the 21st century, while a not-to-exceed temperature target creates no incentive to reduce temperatures below the maximum temperature reached around 2040-2080, even if such a reduction might be achieved at comparatively low cost (Figure S3b).

Finally, we examined if a slower phase-in of the carbon tax during the transition from weak to comprehensive climate policies can alleviate the economic shocks observed in delayed-action scenarios with stringent long-term targets. To this end, we ran Frag2030 scenarios with a more gradual ramp-up of CO₂ price levels from ~30% of the reference price value in 2035 to the full reference price value in 2060. For these scenarios we found that the increase of maximum temperature counteracts the benefit in terms of lower economic challenges, both in terms of aggregated mitigation costs, and in terms of transitional consumption growth reductions. As a consequence these scenarios are in
line with or above the achievability frontier constructed from the default price paths with exponentially increasing price levels.

6 Weak policy scenario

This section provides a detailed description of the weak policy scenario that we introduced as a reference point for the scenarios with a delay in global cooperative mitigation action. It is meant to represent the unambitious end of realistic short and long-term climate policy developments. It was constructed by considering existing climate policies, a weak interpretation of the 2020 Copenhagen Pledges applied to emissions from fossil fuels and industry, and an extrapolation of these targets beyond 2020 based on emissions intensity (GHG emissions per unit of GDP).

We consider three country groups: A group of industrialized countries (Group I, roughly corresponding to the OECD), developing countries without resource exporters (Group II), and fossil resource exporters (Former Soviet Union and Middle East, Group III). Climate policy is assumed to remain fragmented, with no emissions trading between regions until 2020. Limited emissions trading between industrialized and developing countries is allowed after 2020. Under Default technology assumptions, the WeakPol scenario results in 2020 greenhouse gas emission levels of 57.5 Gt CO\(_2\)e, consistent with the emissions estimate obtained in the latest UNEP gap report for the unconditional pledges under lenient rules (UNEP 2012). The specific assumptions for the eleven REMIND regions are described in the following.

Emission targets for industrialized countries (Group I)

For Group I countries, 2020 emission reduction targets are formulated relative to a base year (either 1990 or 2005). Unconditional emission reduction pledges were used where available. If a range for reduction targets is given, we used the lower end (weak interpretation) of pledges. Current long-term (2050) reduction ambitions are assumed to be watered down.

**EU-27:** 2020 ambition on the low end of its Copenhagen Pledges: 20% below 1990. This corresponds to a 13% reduction relative to 2005. Further, we assume that the 2050 emission reduction target is watered down to 40%, and 2100 reductions reach 80%, relative to 1990, respectively.

**USA:** The target to reduce emissions 17% below 2005 in 2020 is assumed not to materialize. Instead, we assume no emission reductions beyond those achieved in the baseline levels. Because of increasing use of natural gas results, baseline emissions in
2020 are 8% below 2005 levels. After 2020, the emissions cap is assumed to decrease by 0.5% per year in the period 2020-50, and 1% per year after 2050.

**Japan:** The 25% emission reduction pledge relative to 1990 is conditional, and therefore assumed not to materialize. Instead, we assumed a 10% emission reduction relative to 1990 by 2020, and a 40% reduction until 2050.

**Rest of the World:** The “Rest-of-the-World” region, largely composed of other states of the “Umbrella Group” (Canada, Australia, New Zealand), plus South Africa, are assumed to achieve combined 2020 emission reductions of 5% relative to 2005. Further, emissions are assumed to decrease by 0.5% per year in the period 2020-50, and 1% per year after 2050.

**Emission targets for emerging economies and developing countries, excluding oil exporting countries**

Developing countries have formulated their 2020 pledges in terms of (a) emissions reductions relative to baseline, or (b) reductions in carbon emission intensity of GDP relative to a base year. In absence of concrete pledges beyond 2020, we assumed yearly emission intensity improvements comparable to those implied by the 2020 pledges.

**China:** China pledged to “lower its carbon dioxide emissions per unit of GDP by 40-45% by 2020 compared to the 2005 level, increase the share of non-fossil fuels in primary energy consumption to around 15% by 2020 and increase forest coverage by 40 million hectares and forest stock volume by 1.3 billion cubic meters by 2020 from the 2005 levels.” China is currently putting in place domestic measures to fulfill this pledge. We therefore assume that it fulfills the ambitious end of the pledge (-45%) for 2020. After 2020, China is assumed to continue to decrease the emissions per unit of GDP by 3% per year.

**India:** India pledged to “reduce the emission intensity of its GDP by 20 to 25% by 2020 in comparison to the 2005 level.” In the REMIND scenarios, this target is not binding. We assume that India follows China in reducing emissions per unit of GDP by 3% per year after 2020.

**Other Asia:** Several other Asian countries have pledged substantial emission reductions relative to baseline—most notably, South Korea (30% relative to baseline) and Indonesia (26% relative to baseline). As a group, we assume other Asian countries to deliver emission reductions of -20% relative to baseline by 2020. After 2020, they are
decrease the emissions per unit of GDP by 3% per year, equal to the decarbonization rate assumed for China.

**Latin America:** Several other Latin American countries have pledged substantial emission reductions relative to baseline—most notably the Brazil (36% below baseline) and Mexico (30% baseline), which account for a substantial share of Latin American emission. We assume that Latin America as a group will deliver 15% emission reduction from non-LUCF emissions. We further assume that LAM will reduce emission intensity by 2.5% per year in 2020-2050, and by 3% per year after 2050.

**Sub-Saharan Africa (excl. South Africa):** Sub-Saharan Africa is assumed not to take any targets before 2020. After 2020-50, a reduction target of emission intensity per unit GDP of 2.5% per year is prescribed. However, this target is not binding, since economic growth exceeds emissions growth by more than 2.5% per year. After 2050, a target on the reduction of emission intensity per unit GDP of 3.5% per year is assumed.

**Emission targets for resource exporters**
The resource exporting REMIND regions (Middle East / North Africa / Central Asia and Russia) are assumed not to have an incentive to take any binding target. Countries of the Middle East have not pledged any emission reduction targets. Russia’s unconditional target of -15 below 1990 is well above projected baseline emissions. Carbon leakage, i.e. higher emissions compared to baseline in Group III countries in response to climate policies in Group I and II countries is allowed.

**Emission control in Sectors**
We assume all Kyoto-Gas Emissions excluding land use, land use change and forestry (LULUCF) to be included in the reduction targets and subject to climate policies. Given higher institutional requirements for monitoring and reporting of land-use related CO_{2} emissions, we assume climate policies to be ineffective in controlling LULUCF emissions. LULUCF emissions are thus assumed not to be subject to carbon pricing, and are not included in the emission reduction targets.

**International Emissions Trading**
In the Weak Policy Scenario, we assume global carbon markets to remain fragmented. Specifically, the following rules for the trade of emission allowances and intertemporal flexibility in the mitigation effort were assumed to apply:

- No emissions trading, nor banking or borrowing is permitted until 2020
- After 2020, unrestricted emissions trading between members of Group I
• After 2020, unrestricted emissions trading between members of Group II
• The total net import of Group I (from Group II) is restricted to 20% of the combined mitigation requirement of Group I (i.e., the difference between baseline emissions and emission allowances under the cap).
• Full when-flexibility is allowed within the periods 2020-2050 and 2050-2100.
• Excess emission allowances from 2020-2050 can be banked to the 2050-2100 period, but no borrowing from the second period is allowed in the first period.
Figure S1: Effect of different near-term climate policy regimes on the development of (a) the value of emission permits under the global cap over time, and (b) the global energy price index. For the mitigation scenarios Immediate, Frag2015, Act2030 and Frag2030 cumulative emissions budget of 2500 GtCO₂e were considered.
Figure S2: Temperature-cost-tradeoff curves showing the effect the technology availability on (a) carbon market value, and (b) energy price increase (Frag2015 scenario).
Temperature targets (maximum 2010-2100 temperatures) reached with a 67% likelihood (lower axis) or 50% likelihood (upper axis) are shown. Numbers indicate shift in terms of $\Delta T_{67}$. 

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Figure S3: The sensitivity of aggregated mitigation costs to the choice of discount rate in the inter-temporal aggregation (cf. Fig. 2a of the main paper).
Figure S4: The effect of different climate target implementations examined for the example the Frag2030 scenario with Default technology assumptions. In addition to exponential carbon price pathways (which are used for the analysis in the main paper), we show a scenario with a pre-scribed 2010-2100 GHG emission budget (purple circle), an explicit not-to-exceed temperature target (blue diamonds), and price paths with a slower phase-in of carbon prices. The results show that the temperature-cost trade-off curves derived based on exponential price paths are a robust indicator of the efficient achievability frontier for a given scenario setup.
Figure S5: Correlation between temperature increases not exceeded with 67% and 50% likelihood for (a) maximum 2000-2100 temperatures, and (b) 2100 temperatures. Each individual data point corresponds to one climate mitigation scenario, with different colors indicating different assumptions along the delay dimension, and different markers correspond to different technology assumptions.
Effect of timing on AMC (Default tech)

Effect of technology on AMC (Frag2015)

Effect of timing on TGR (Default tech)

Effect of Technology on energy prices

Figure S6: Temperature-cost tradeoff curves considering 2100 temperature levels. Grey lines indicate corresponding trade-off curves that consider maximal 2000-2100 temperatures. The left column shows the effect of mitigation timing, the right column the effect of technology availability. (a), (b) show aggregated mitigation costs, (c) shows transitional growth reductions, and (d) shows the maximum climate-policy induced decadal energy price increase. Note that for the NoCCS and LimBio scenarios, maximal temperatures are reached in 2100, therefore colored lines (2100 temperature) lie on top of the grey lines (maximal 21st century temperature).
Figure S7: Overview of the combined effects of mitigation timing and technology availability on achievability of not-to-exceed targets and 2100 temperature target that allow for temporary overshoot. Graphs show economic challenges (color shading) in terms of aggregated carbon market value (left panels a,c), and short-term energy price increase (right panels b,d), as a function maximal 2010-2100 temperature increase (upper panels) or 2100 temperature increase (lower panel). Dark grey areas at the base of bars indicate temperature target levels that were not achieved with the range of carbon price paths assumed.
Figure S8: Relationship between maximum surface air temperatures during the 21st century (horizontal axis) and 2100 surface air temperatures (vertical axis) for the full set of 171,000 climate model realizations of the 285 REMIND scenarios. The red histogram shows the distribution of maximal 2000-2100 temperatures that result in a temperature of 1.5°C in 2100.
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Chapter 3

Implications of Weak Near-Term Climate Policies on Long-Term Mitigation Pathways*

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Implications of weak near-term climate policies on long-term mitigation pathways

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Abstract While the international community has agreed on the long-term target of limiting global warming to no more than 2 °C above pre-industrial levels, only a few concrete climate policies and measures to reduce greenhouse gas (GHG) emissions have been implemented. We use a set of three global integrated assessment models to analyze the implications of current climate policies on long-term mitigation targets. We define a weak-policy baseline scenario, which extrapolates the current policy environment by assuming that the global climate regime remains fragmented and that emission reduction efforts remain unambitious in most of the world’s regions. These scenarios clearly fall short of limiting warming to 2 °C. We investigate the cost and achievability of the stabilization of atmospheric GHG concentrations at 450 ppm CO₂e by 2100, if countries follow the weak policy pathway until 2020 or 2030 before pursuing the long-term mitigation target with global cooperative action. We find that after a deferral of ambitious action the 450 ppm CO₂e is only achievable with a radical up-scaling of efforts after target adoption. This has severe effects on transformation pathways and exacerbates the challenges of climate stabilization, in particular for a delay of cooperative action until 2030. Specifically, reaching the target with weak near-term action implies (a) faster and more aggressive transformations of energy systems in the medium term, (b) more stranded investments in fossil-based capacities, (c) higher long-term mitigation costs and carbon prices and (d) stronger transitional economic impacts, rendering the political feasibility of such pathways questionable.

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1 Introduction

In the Copenhagen Accord, the international community agreed on the long-term target of limiting the increase of global mean temperature to no more than 2 °C, relative to pre-industrial levels. The subsequent Cancun and Durban climate conferences reaffirmed this target. Reaching the 2 °C target with high likelihood implies a tight limit on future anthropogenic greenhouse gas (GHG) emissions. Various reports have concluded that pledged national 2020 reduction targets fall short of the reductions required to meet the 2 °C target in an inter-temporally cost-optimal way (UNEP 2010, 2011; Rogelj et al. 2010, 2011).

So far, model-based research on the implications of weak near-term policies in the context of ambitious long-term mitigation targets is in its infancy. The EMF-22 study explored how international participation affects the attainability of different climate targets and concluded that a failure to develop a comprehensive, international approach will constrain efforts to meet ambitious climate targets (Clarke et al. 2009). As part of the same project, Calvin et al. (2009a) analyzed the implications of low stabilization in the context of fragmented climate policy regimes on energy and land-use systems. The RECIPE study explored the implications of a delay in climate mitigation, by one or several world regions, in terms of global costs and feasibility as well as incentive structures (Jakob et al. 2012; Luderer et al. 2012a). Van Vliet et al. (2012) explored the high and low ends of the possible realizations outlined by the Copenhagen Pledges and their implications for the achievability of the 2 °C target. Even the ambitious ends of the 2020 pledges resulted in substantial cost increases compared to the least-cost pathways with immediate action. Van Vliet et al. concluded that with weaker emissions reductions in 2020, keeping global warming below 2 °C is unlikely.

This study uses three integrated assessment models to advance the understanding of future climate agreements. It goes beyond the simple assessment of the gap between near-term emission reduction pledges and reductions implied by pathways with optimal timing by exploring the consequences of agreeing on low stabilization targets only after 2020 and 2030. The study design is described in Section 2. Since a number of energy and climate policies are already under way, this study defines a weak policy scenario as the pessimistic, low end of the plausible near-term climate policies and extrapolates their level of ambition to the medium- to long-term future. Section 3 analyzes implications of weak and immediate action scenarios for emission pathways. In Section 4, we study how the timing of mitigation affects energy system transformations. In Section 5, we explore the economic implications of weak near-term action. Section 6 discusses the results and conclusions.

2 Study design

This study is based on a subset of the scenarios conducted in the RoSE study (Kriegler et al., Submitted for publication in this special issue). The subset consists of the following five harmonized scenarios:

A. No-policy baseline scenario (BASELINE)

In this counter-factual scenario, the development of a world without any climate policies after 2010 is considered. The models have been harmonized using the RoSE default assumptions (cf. Kriegler et al., Submitted for publication in this special issue) for (1) population scenarios, (2) regional GDP growth, and (3) fossil resources.\footnote{This scenario is identical to BAU DEF presented in the RoSE synthesis paper (Kriegler et al., Submitted for publication in this special issue).}
B. Weak-policy baseline scenario (WEAK-POL)

This scenario is designed as a reference scenario that includes weak climate policies. It is meant to represent the unambitious end of current short- and long-term climate policy trends. It was constructed by considering existing climate policies, a weak interpretation of the 2020 Copenhagen Pledges, and an extrapolation of these targets beyond 2020 based on emissions intensity (GHG emissions per unit of GDP). Three country groups are considered: industrialized countries (Group I), developing countries excluding resource exporters (Group II), and fossil resource exporters of the former Soviet Union and Middle East (Group III). Climate policy is assumed to remain fragmented, with no emissions trading between regions until 2020. Limited trading of emissions between industrialized and developing countries is allowed after 2020. It is assumed that resource-exporting countries will not adopt any binding targets. Furthermore, it is assumed that land-use emissions will not be subject to carbon pricing. A detailed description of the assumptions and methodology used in the WEAK-POL scenario is provided in the supplementary material (SM2). Section 3 presents the resulting emission and energy system pathways, as well as the climate outcomes.

C. Immediate action (IMMEDIATE)

This scenario considers immediate, globally coordinated, cooperative climate policies that are aimed at stabilizing GHG concentrations at 450 ppm CO₂e by 2100. Temporary overshooting of the concentration target is permitted. The 450 ppm CO₂e target is consistent with a greater-than–50 % likelihood that temperatures will stabilize below 2 °C (Meinshausen et al. 2011). This scenario incorporates full “what,” “where,” and “when” flexibility. A global carbon market is established, and emission reductions are distributed in a cost-optimal way across time and across various source sectors and GHGs.

D. Weak action until 2020 (WEAK-2020) and weak action until 2030 (WEAK-2030)

The WEAK-2020 and WEAK-2030 scenarios assume that the adoption of a global agreement aimed at stabilizing GHG concentrations at 450 ppm CO₂e by 2100 will be delayed until 2020 or 2030, respectively. Before this, countries will follow the WEAK-POL baseline without anticipating future climate policies that are more stringent. Once the agreement is adopted, a global carbon market is installed, thus ensuring a cost-efficient regional allocation of emission reduction efforts.

This study used three state-of-the-art integrated assessment models. Since socio-economic drivers and fossil fuel availability are harmonized, differences in the results (discussed in the subsequent sections) reflect different structural assumptions, particularly in terms of the dynamics of energy, land-use and climate systems. Detailed descriptions of the models are available in the supplementary materials provided by Kriegler et al. (submitted for this issue). Notable model characteristics that are particularly relevant for this study are listed in the paragraphs below. The present scenarios assumed that all the low-carbon technologies represented in the models were available. In particular, technologies for combining bioenergy with carbon capture and storage (BECCS) are available in all three models.

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2 This scenario is identical to 450 DEF presented in the RoSE synthesis paper (Kriegler et al., Submitted for publication in this special issue).

3 While the climate modules of all three models are calibrated to a climate sensitivity of 3 °C for a doubling of CO₂ concentrations relative to pre-industrial levels, they differ in terms of other characteristics, such as the carbon cycle response, or transient climate response.
**GCAM** is a multi-regional market equilibrium model. It includes a detailed representation of the energy system and of the agriculture-land-use system, and captures the interactions of these two sectors (Wise et al. 2009). The model is dynamic-recursive, thus assuming that economic agents are myopic. Technological innovation is exogenously prescribed. Capital stock in the electricity and refining sectors are assumed to be long-lived. However, premature retirement of capital is allowed when the market price does not cover operating costs. GCAM includes no explicit constraints on the expansion of capital stock from period to period or the retirement of capital stock. In the GCAM version used for RoSE, biomass availability is limited to ~210 EJ/yr globally.

**REMIND** is an energy-economy model composed of a macro-economic growth module coupled with an energy system module with considerable detail in the representation of capital stocks in energy supply technologies (Bauer et al. 2013; Leimbach et al. 2010; Luderer et al. 2012c). The model is solved as an inter-temporal optimization problem, thus assuming perfect foresight by economic agents. Technological innovation in wind and solar energy supply technologies are treated endogenously via global learning curves, which give rise to path dependencies and technology spillover effects. The premature retirement of coal- and gas-fired power plants before the end of the technical lifetime is assumed to be possible, but is constrained to 4 %/yr of installed capacity. The rapid ramp-up of technologies is subject to a cost penalty (i.e., “adjustment costs”), which scales with the square of the rate of change in new capacities. In the REMIND version used for RoSE, biomass availability is limited to 200 EJ/yr.

Similar to REMIND, **WITCH** is an optimization model that assumes the perfect foresight behavior of economic agents. It integrates a macro-economic growth model and an energy system module that characterizes power-generating investments and final energy uses (De Cian et al. 2013; Bosetti et al. 2006). WITCH characterizes the endogenous nature of technical progress in the energy sector and accounts for international and inter-temporal technology externalities generated by research and development (R&D) investments and technology deployment. R&D investments enhance energy efficiency and facilitate the penetration of innovative low-carbon technologies in power generation as well as final energy use (breakthrough technologies). Further cost-reductions related to learning-by-doing are considered for the breakthrough technologies as well as for wind power. Early retirement of power generating technologies is allowed without specific limitations.

### 3 Emissions pathways with weak near-term climate policies

This section explores the emission pathways of the WEAK-POL scenario and the various 450 ppm stabilization scenarios, and analyses their implications for changes in global mean temperature and radiative forcing. Despite the unambitious near-term policies in the WEAK-2020 and WEAK-2030 scenarios, all the models find it feasible to reach the target by 2100 even if cooperative, ambitious action is delayed until 2020 or even 2030, albeit with more aggressive emission reductions within a rather short time frame.

The climate policies assumed in the WEAK-POL scenario result in a significant decrease of emission reductions relative to the BASELINE scenario without climate policies. Global emissions are between 3 % (REMIND) and 8 % (WITCH) below the baseline level in 2020 and between 16 % (REMIND) and 18 % (WITCH) below baseline levels in 2050.³⁴ Due to

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³ Although reference GDP, population, and fossil fuel availability have been harmonized across models, baseline emissions still differ across models, reflecting different structural and technology assumptions.
the fragmented nature of climate policy in the WEAK-POL scenario, regionally differentiated carbon prices emerge (see supplementary material, Figure SM 2.1). In 2030, carbon prices in the industrialized countries are between two (REMINd and WITCH) and three-times (GCAM) higher than those in developing countries in 2030. As a consequence, the highest relative reduction of cumulative emissions between 2010 and 2050 occurs in the industrialized countries (Group I), while the developing countries (Group II) achieve relatively lower reductions (Figure SM3.1). Resource exporting countries (Group III) slightly increase their emissions compared to the baseline as a result of carbon leakage, wherein the overall consumption of fossil resources in Group III increases as prices decrease due to the climate policies undertaken in the other two country groups.

The emission reductions realized in WEAK-POL are far smaller than what is required to achieve 450 ppm CO₂e stabilization (Fig. 1). Cumulated Kyoto gas emissions from 2010 to 2100 are between 5,500 and 5,800 Gt CO₂e, 20–25 % below baseline levels. This compares to cumulative budgets in the range of 2,100–2,300 Gt CO₂e in the 450 ppm CO₂e stabilization scenarios. The resulting forcing levels in 2100 lie between 5.3 (WITCH) and 5.9 W/m² (GCAM), roughly 1 W/m² below baseline levels. Global mean temperature continues to rise throughout the century, reaching about 3.5 °C by 2100. The climate policies assumed to be implemented in this scenario are thus much too weak to achieve the 2 °C target.

The three models show different emissions trajectories for the IMMEDIATE scenario. In REMIND and WITCH, emissions peak in 2010 and decline gradually at a rate of 1–3 %/year. The GCAM trajectory is characterized by a late and high peak, with emissions remaining above 2005 levels until 2035, with a higher rate of emissions reductions afterwards. This is because of the more rapid deployment of BECCS in future years, which allows for negative

Fig. 1 Global CO₂ emission trajectories for the BASELINE, WEAK-POL, WEAK-2020, WEAK-2030, and IMMEDIATE policy scenarios
emissions. In the WEAK-2020 scenario, global GHG emissions peak between 50 GtCO₂ (WITCH) and 57 GtCO₂e (GCAM), which is 22–33 % higher than the emissions levels in the IMMEDIATE scenario. The different emission patterns in the IMMEDIATE scenario affect the size of the gap between IMMEDIATE and the weak action scenarios in 2020 and 2030.

Despite the higher emission levels in the WEAK-POL scenarios compared to IMMEDIATE, all three models find it feasible to achieve the 450 ppm CO₂e stabilization level by 2100 even when cooperative action does not start until 2020 or even 2030. With the exception of the WEAK-2020 scenario in GCAM, the delayed introduction of ambitious and cooperative climate policies results in much more aggressive emission reductions than in the IMMEDIATE scenario. For WEAK-2030, GCAM reduces emissions by about 60 % between 2030 and 2040, WITCH by about 50 %, and REMIND by 40 %. However, the aggressive reductions required after the transition from the weak to the ambitious climate policy regime would imply structural changes in energy supply and demand at an unprecedented pace, causing potentially severe economic impacts, as discussed in Sections 4 and 5.

Due to the long residence time of GHGs in the atmosphere, the effects of anthropogenic emissions on the climate are primarily a function of the cumulative emissions budget (Meinshausen et al. 2009). Limiting the GHG concentration to a specified level consequently constrains total GHG emissions throughout the coming century. This property also holds for the various stabilization scenarios considered in this study: we find that the GHG budget reaching 450 ppm CO₂e by 2100 is almost independent of the timing of mitigation action (Figure SM3.1). Therefore, emissions reductions after the adoption of the climate stabilization target are steeper in the weak near-term climate policy scenarios, while long-term emission levels tend to be lower than in the case of immediate action (Fig. 1).

The models differ regarding the point in time at which the WEAK-2020 scenario catches up with the emission levels of the immediate action scenario. While the emissions gap between these two scenarios closes by 2025 in WITCH and 2030 in GCAM, in the REMIND WEAK-2020 emissions do not reach the level of the IMMEDIATE scenario until 2040. According to all the models, the difference in long-term emissions between the WEAK-2020 and the IMMEDIATE scenarios is rather small (well below 1 GtCO₂/yr). In other words, the additional effort to compensate for excess emissions before the crossover point is moderate.

The discrepancy with the immediate action scenario is much larger in the WEAK-2030 scenario than in the WEAK-2020 scenario. By 2030, emissions in REMIND and WITCH are approximately 70 % above those of the immediate action case. For GCAM, the difference is 31 %. Emission reductions after the adoption of the climate target are much steeper than in the IMMEDIATE scenario and even the WEAK-2020 scenario. GCAM and WITCH feature emission reduction rates up to 10 %/year between 2030 and 2040, with emissions dropping below the level of the immediate action and WEAK-2020 scenarios. This reflects different assumptions on the rate at which fossil-based capacities can be retired, and new, low-carbon energy technologies are phased-in. Path dependencies in the REMIND energy system are more pronounced than in WITCH and GCAM (cf. Section 4.2); therefore, emissions reductions after 2030 are not as steep as in GCAM and WITCH. As a result, the excess in cumulative emissions until 2050 in the WEAK-2030 scenario compared to the IMMEDIATE scenario is higher in REMIND than in WITCH and GCAM (Figure SM3.1).

5 The cumulative budgets for the weak actions scenarios are slightly higher than in the immediate action scenario. Due to carbon cycle dynamics, a smaller share of emissions that occur early in the century remain airborne, compared to emissions that occur at a later point in time.
To make up for the excess near-term emissions, the long-term emissions in the REMIND WEAK-2030 scenario are considerably lower than in the IMMEDIATE and WEAK-2020 scenarios.

For the IMMEDIATE, WEAK-2020, and WEAK-2030 scenarios, a 2100 forcing level of 2.6 W/m² is prescribed as a climate target, but no limit on the overshooting is defined. Moreover, the models use different climate system representations. Therefore, the scenarios are not equivalent in terms of the transitory climate effects. Differences in near-term emissions have an effect on the peak levels of radiative forcing and temperature (Fig. 2). In all three models, weak action results in higher radiative forcing in the near-term. This difference is the greatest in REMIND, where radiative forcing peaks at 3.2 W/m² in the IMMEDIATE scenario, and at 3.6 W/m² in the WEAK-2030 scenario. The resulting higher rates of temperature change, higher peak CO₂ concentrations as well as temperature overshooting may have implications for climate impacts, including the likelihood of triggering tipping points.

The overshooting of forcing also results in a slight peak in global mean temperatures. This effect is more pronounced in the WEAK-2020 and WEAK-2030 scenarios than in the IMMEDIATE scenario. As a result, the 2 °C level is temporarily exceeded in REMIND and WITCH.

4 Implications for the transformation of energy systems

Due to its dominant share in emissions, the energy system has to bear the bulk of the climate mitigation effort. This section analyses the effect of weak policies on global energy systems, and implications of delayed cooperative action on the energy system transformation.

4.1 Primary energy supply

The effect of weak climate policies on primary energy supply is depicted Fig. SM4.1 (right row). In all three models, the adoption of weak climate policies results in a sizable reduction in conventional coal use in the medium- and long-term. By 2050, coal use without CCS is 80 EJ (REMIND), 90 EJ (WITCH) and 130 EJ (GCAM) lower than in the baseline. Reductions in oil and gas are less significant. For all models, energy supply from biomass and nuclear is higher than the baseline. GCAM projects considerable deployment of carbon capture and storage (CCS) already in the first half of the century. The decrease of primary energy

![Fig. 2](image_url)  
**Fig. 2** a Maximum radiative forcing and (b) maximum transient global mean temperature increase in 2010–2100
demand caused by weak climate policies is the most pronounced in WITCH, where R&D investments can improve energy efficiency.

The consumption of fossil energy in the IMMEDIATE scenario is substantially lower than in the weak action scenarios (Fig. 3, left). In particular, coal use without CCS declines immediately after 2010 and a gradual but substantial phase-in of low-carbon energy carriers and technologies occurs simultaneously. In 2020, fossil energy use without CCS is 60 EJ (GCAM), 80 EJ (WITCH), and 100 EJ (REMIN) lower than in the weak action scenarios (Fig. 3, right). By 2030, the gap in fossil energy-use widens to between 180 (GCAM) and 240 EJ (REMIN). Similarly, low carbon energy deployment in the immediate action scenario exceeds that of the weak action scenarios by 40 EJ (WITCH), 60 EJ (GCAM), and 110 EJ (REMIN). The diversity of energy system transformations found in the model results shows that there are several alternative pathways with different technology choices towards the same common long-term climate target.

In case of a delay of ambitious cooperative action, the divergent development between the weak action and immediate action scenarios prior to target adoption poses a two-fold challenge for the development of the energy system after target adoption. First, at the time of target adoption, the energy system’s capital stock is characterized by higher fossil capacities and fewer low-carbon capacities. Second, in order to reach the same stabilization target, the excess emissions from the weak policy period must be compensated by lower cumulative emissions during the remainder of the century (see also Figures SM4.2 and SM 4.3).
Climate policy renders many pre-existing fossil installations unprofitable, resulting in early retirements of capacities. In IMMEDIATE, for example, a substantial volume of fossil capacities for electricity generation are stranded, as shown in Fig. 4. While the models agree that unused capacities increase in the WEAK-2020/WEAK-2030 scenarios, they exhibit different timing and scale in terms of the retirement and replacement of excess fossil capacities. This is particularly evident in the WEAK-2030 scenario. In GCAM and WITCH, the introduction of a high, globally uniform carbon price results in the sudden retirement of a major share of conventional fossil capacities. As a consequence, coal, oil, and gas use in the WEAK-2030 scenario fall to levels below those of the IMMEDIATE scenario by 2035 (Fig. 3). REMIND is characterized by stronger path dependencies and a slower phase-out of fossil fuels, reflecting the assumption of moderate premature retirement of coal- and gas-fired power plants (see Section 2). Conventional fossil energy use in the WEAK-2030 scenario remains above that of the IMMEDIATE scenario until 2050. The supplementary materials (SM5) provide a detailed discussion of stranded investments under different climate-policy-timing scenarios.

Moreover, patterns regarding the phase-in of low-carbon technologies after weak near-term action differ across models. In GCAM, weak near-term climate policy results in more rapid and aggressive deployment of bioenergy with CCS (BECCS) after adoption of the climate target. Among the three models, GCAM is most optimistic about the availability of CCS storage potentials (see also Kriegler et al., Submitted for publication in this special issue). Furthermore, nuclear energy and natural gas, in combination with CCS, are deployed at a higher level than in the IMMEDIATE scenario. By contrast, the use of coal with CCS is lower because the carbon price applied to the residual emissions is higher in the WEAK scenarios, which drives up the cost of coal with CCS. In REMIND, the higher carbon prices after 2030 in the weak action scenarios result in higher electrification and deployment of non-biomass renewables compared to the IMMEDIATE scenario. Differences in bioenergy use are small, since all stabilization scenarios result in biomass deployment close to the maximum potential. In WITCH, the deployment of BECCS, nuclear, and wind increases slightly. The reduction of energy demand relative to the baseline scenario is more pronounced in WITCH than in the other models (see Section 4.2).

4.2 Energy demand reductions and decarbonization of supply

Energy-related emission reductions can be achieved by reducing total final energy demand, by reducing the amount of CO₂ emitted per unit of final energy produced (carbon intensity), or through a combination of both. From a meta-perspective, energy system transformations can thus be characterized in terms of the relative contributions of these two factors. Figure 5 presents the final energy demand and carbon intensity for the climate stabilization scenarios as well as the WEAK-POL and BASELINE scenarios. The models agree that the adoption of a stringent climate policy target results in a strong reduction of energy demand relative to the baseline—which is particularly significant in the short-term—as well as a strong and continuous decarbonization trend. Nevertheless, differences across models exist in the relative importance of demand reduction and decarbonization and the pace at which they can be achieved.

6 In GCAM, BECCS and Gas CCS deployment in the weak action cases is lower than in the immediate action cases after 2080. For both technologies, the cost of electricity generation is higher in the WEAK action cases after 2080, due to higher bioenergy prices in the case of BECCS and the higher carbon prices applied to residual emissions in the case of Gas CCS.
The adoption of ambitious cooperative action results in an abrupt increase of carbon prices (cf. Section 5). The energy supply in GCAM is most responsive to this price shock, with very high decarbonization rates after target adoption. Early retirement of existing fossil capacities (see Section 4.1 and SM5) and rapid up-scaling in the deployment of carbon-free technologies enable a fast reduction of carbon intensity. This pattern is particularly prominent in the WEAK-2030 scenario. Energy demand reductions, by contrast, are less important than in the other two models.

In WITCH, carbon intensity is reduced at a lower rate and long-term carbon intensity levels are higher than in the other two models. In the climate policy scenarios, a substantial level of energy-related emissions remain, and the deployment of bioenergy in combination with CCS is considerably smaller than in GCAM and REMIND. While WITCH is less optimistic about supply-side decarbonization options, it features a larger contribution from the reduction of final energy demand, with a more pronounced contraction of final energy. Induced innovation provides an additional channel for demand side energy intensity improvement, which, along with the substitution between capital and energy in the macroeconomic production function, reduces the amount of final energy per unit of output.

Fig. 4 Global fossil electricity generation capacities that become unused in different climate policy scenarios

Fig. 5 Global (a) final energy demand and (b) carbon intensity of final energy across the different scenarios
produced and in a more pronounced contraction of final energy (see also De Cian et al. 2013).7

The decarbonization of the REMIND energy system is characterized by longer transition time scales after climate target adoption. This is due to the constraint on the rate of premature retirement of fossil capacities, which is assumed to be limited to 4 %/yr, and the cost penalty for fast up-scaling of low-carbon options. The contribution of reductions in energy demand is sizeable, but smaller than in WITCH. As in the other two models, the price shock arising from the high carbon prices in the WEAK-2030 scenario results in a short-term contraction of final energy demand to a level below that in the other two stabilization scenarios.

5 Carbon prices and climate policy costs

The IMMEDIATE action scenario describes an optimal pathway towards the prescribed climate stabilization target, and therefore results in the lowest cumulative discounted mitigation costs. Weak near-term action results in a deviation from the least-cost pathway, and thus has a different carbon price and mitigation cost pattern. This section analyzes the implications of the timing of mitigation efforts on the evolution of carbon prices and costs.

Figure 6c presents the intertemporally aggregated global climate policy costs expressed as a fraction of global economic output.8 The mitigation costs, aggregated over 2010–2100, amount to 1.4 % (REMIND), 1.5 % (GCAM), and 2.5 % (WITCH) of global economic output in the IMMEDIATE scenario.9 By contrast, climate policy costs amount to a few tenth of a percent for a continuation of weak, fragmented climate policies throughout the century (WEAK-POL scenario). The differences in mitigation costs reflect differences in the responsiveness of models to climate policies (Kriegler et al. 2013). In GCAM and REMIND, more emissions reduction options are available at lower cost levels, while abatement options are more scarce and costly in WITCH.

A delay of comprehensive emission reductions results in an increase in aggregated costs that is relatively small for WEAK-2020, but more significant for WEAK-2030. For this scenario, aggregated costs are between 11 % (GCAM) and 45 % (REMIND) higher than in the IMMEDIATE scenario. The differences in cost penalties for delayed action relate directly to differences in short-term flexibilities and path-dependencies between GCAM (high short-term flexibility), WITCH (medium short-term flexibility) and REMIND (stronger path dependencies).

Regarding the evolution of costs over time, all models indicate a continuous increase in global mitigation costs as a fraction of GDP for the climate policy scenarios (Fig. 6a). This means that climate policies reduce the rate of income growth relative to the baseline. In the IMMEDIATE scenario, the introduction of climate policy lowers the rate of income growth by 0.16 %/yr or less in the first two decades (Fig. 6d). In the WEAK-2030 scenario, the radical emission reductions within a relatively short period of time result in a marked jump in policy costs. As shown in Fig. 6d, the reduction of income growth rates in the decade after climate policy adoption is considerably higher for the WEAK-2020 scenario than for IMMEDIATE, and more than doubles for WEAK-2030.

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7 The mechanism of R&D in energy efficiency is not represented in REMIND and GCAM.
8 It is important to note that we quantify the costs of reducing emissions, but do not consider the benefits of avoided climate damages.
9 In REMIND and WITCH, mitigation costs are calculated as consumption losses relative to the baseline. In GCAM, mitigation costs were calculated as the area under the marginal abatement cost curve (Calvin et al. 2009b). A discount rate of 5 % was used for the intertemporal aggregation of mitigation costs.
Carbon prices quantify the marginal costs of emissions reductions. Due to their influence on energy prices, CO₂ prices affect the incidence of mitigation costs on households, businesses, and industry. CO₂ prices are also an important driver of the distribution of mitigation costs among nations under a global cap and trade system (Luderer et al. 2012b). Figure 6b depicts the evolution of carbon prices over time. In the IMMEDIATE scenario, carbon prices are approximately 30$/tCO₂ in 2015 and increase nearly exponentially over time. The transition from fragmented, unambitious climate policy to a cooperative, ambitious climate policy regime results in an abrupt increase of carbon prices (Fig. 6b). To compensate for weak near-term action, carbon prices after target adoption are higher than in the IMMEDIATE scenario. For the WEAK-2030 scenario, carbon prices jump from 10 to 30 $/tCO₂ in 2030 to between 100 $/tCO₂e (GCAM) and 250 $/tCO₂ (WITCH) in 2035.

6 Discussion and conclusions

Our analysis shows that continuing climate policies at the current level of ambition would fail to have a significant impact on climate change and warming. In particular, such weak policies are insufficient to stabilize GHG emissions at a level that is consistent with the long-term target of limiting global temperature increase to no more than 2 °C, relative to pre-industrial levels. At the same time, our analysis suggests that mitigation pathways reaching 450 ppm CO₂e by 2100 are possible with the abatement flexibility in the models, even with a further delay of cooperative and comprehensive mitigation action.
However, our results show that weak near-term action exacerbates the 450 ppm CO₂e challenge, which requires fundamental transformations even if started immediately. The impacts of delaying comprehensive action until 2020 are noticeable, and become very substantial if action is delayed until 2030. In delayed action scenarios we observe a steep increase of carbon prices during the transition from unambitious, fragmented climate policies to an ambitious coordinated climate regime, more radical decarbonization rates of energy supply, more ambitious reductions of final energy demand, and greater stranded investments resulting from the early retirement of fossil capacities. The contraction of mitigation action to a short time horizon imposes a major shock to economic systems, and reduces income growth markedly in the decade after target adoption. For reasons of political acceptability, the phase-in of climate policies will presumably have to be slower in the real world than in the stylized scenarios considered here, thus further increasing the long-term mitigation challenges. In summary, in view of the rapid decarbonization rates and strongly increased mitigation challenges observed in the WEAK-2030 scenario, it can be expected that the political and social acceptability of 2 °C mitigation pathways with a prolonged delay of action will be called into question. The determination of acceptability is, of course, a political question and outside the scope of this paper.

Our study reveals several areas of further research needs. The scenarios considered in this study all assume that the full set of mitigation technologies represented in the models is available. Some of these technologies, such as CCS, are not yet fully mature. Other supply-side options, such as large-scale bioenergy use or nuclear power, face public opposition. The effect of weak action in the case of incomplete technology portfolios is yet to be explored. The models exhibit a high degree of flexibility in reacting to the carbon price shock in the weak near-term action scenarios. Different assumptions regarding path-dependencies explain some of the differences in the results of the three models used in this study. More research is required to explore path-dependencies and inertias in energy systems and land-use, in order to qualify the plausibility of such developments. More detailed studies on the interrelation between the representation of path dependencies and the impact of unambitious near-term action are required, ideally by comparing a larger number of structurally different models. Finally, our results show that for a given long-term stabilization target, weak near-term action results in higher overshooting of GHG concentrations and global mean temperatures than immediate action, as well as higher rates of climate change. Further climate impact research is required to clarify the incremental impacts that result from such overshooting pathways.

Acknowledgments  This work was supported by Stiftung Mercator in the context of the RoSE project.

References


Supplementary Material to

Implications of weak near-term climate policies on long-term mitigation pathways
Gunnar Luderer, Christoph Bertram, Katherine Calvin, Enrica De Cian, Elmar Kriegler
This section provides a detailed description of the weak policy scenario that we introduced as a reference point for the scenarios with a delay in global cooperative mitigation action. It is meant to represent the unambitious end of realistic short and long-term climate policy developments. It was constructed by considering existing climate policies, a weak interpretation of the 2020 Copenhagen Pledges, and an extrapolation of these targets beyond 2020 based on emissions intensity (GHG emissions per unit of GDP).

We consider three country groups: A group of industrialized countries (Group I, roughly corresponding to the OECD), developing countries without resource exporters (Group II), and fossil resource exporters (Former Soviet Union and Middle East, Group III). Climate policy is assumed to remain fragmented, with no emissions trading between regions until 2020. Limited emissions trading between industrialized and developing countries is allowed after 2020. The resulting 2020 emission levels are roughly consistent with the range of emissions estimate obtained in the latest UNEP gap report (42). The specific assumptions for the various world regions are presented in the following.

Emission targets for industrialized countries (Group I)

For Group I countries, 2020 emission reduction targets are formulated relative to a base year (either 1990 or 2005). Unconditional emission reduction pledges were used where available. If a range for reduction targets is given, we used the lower end (weak interpretation) of pledges. Current long-term (2050) reduction ambitions are assumed to be watered down. An overview of the assumed reduction targets is provided in Table SM1.1.

**EU-27:** 2020 ambition on the low end of its Copenhagen Pledges: 20% below 1990. This corresponds to a 13% reduction relative to 2005. Further, we assume that the 2050 emission reduction target is watered down to 40%, and 2100 reductions reach 80%, relative to 1990, respectively.

**EFTA+** (Switzerland, Norway, Iceland, + Mini States): Assumed to follow EU.

**USA:** The target to reduce emissions 17% below 2005 in 2020 is assumed not to materialize. Instead, we assume a 5% emission reduction relative to 2005. After 2020, the emissions cap is assumed to decrease by 0.5% per year in the period 2020-50, and 1% per year after 2050.

**Canada:** Assumed to follow the US.

**Australia and NZ:** Assumed to reduce 2020 emissions (excl. LULUCF) by 5% relative to 2005. Emissions reductions of 0.5% per year between 2020 and 2050 and 1% per year after 2050 are assumed.
Japan: The 25% emission reduction pledge relative to 1990 is conditional, and therefore assumed not to materialize. Instead, we assumed a 10% emission reduction relative to 1990 by 2020, and a 40% reduction until 2050.

<table>
<thead>
<tr>
<th>Percent reduction</th>
<th>2020 rel to 1990</th>
<th>2020 rel to 2005</th>
<th>2050 rel to 1990</th>
<th>2050 rel to 2005</th>
<th>2100 rel to 1990</th>
<th>2100 rel to 2005</th>
</tr>
</thead>
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<td>EU</td>
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<td>-13%</td>
<td>-40%</td>
<td>-34%</td>
<td>-80%</td>
<td>-78%</td>
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<td></td>
<td></td>
</tr>
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<td>-51%</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Canada</td>
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<td>-18%</td>
<td>-51%</td>
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<tr>
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<td>-18%</td>
<td>-51%</td>
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</tr>
</tbody>
</table>

Table SM1.1 Emissions reduction targets for industrialized countries assumed in the WEAK-POL scenario. Primary assumptions are highlighted in bold font.

Emission targets for emerging economies and developing countries, excluding oil exporting countries

Developing countries have formulated their 2020 pledges in terms of (a) emissions reductions relative to baseline, or (b) reductions in carbon emission intensity of GDP relative to a base year. In absence of concrete pledges beyond 2020, we assumed yearly emission intensity improvements comparable to those implied by the 2020 pledges. The emission reduction targets for Group II countries and regions are listed in Table SM1.2. The underlying rationale is as follows:

China: China pledged to "lower its carbon dioxide emissions per unit of GDP by 40-45% by 2020 compared to the 2005 level, increase the share of non-fossil fuels in primary energy consumption to around 15% by 2020 and increase forest coverage by 40 million hectares and forest stock volume by 1.3 billion cubic meters by 2020 from the 2005 levels.” China is currently putting in place domestic measures to fulfill this pledge. We therefore assume that it reaches at least the pledged emissions intensity reductions of -40% for 2020. After 2020, China is assumed to continue to decrease the emissions per unit of GDP by 3% per year.

India: India pledged to “reduce the emission intensity of its GDP by 20 to 25% by 2020 in comparison to the 2005 level.” We assume that at least the 20% reduction in emissions intensity is reached. Like China, we assume a further reduction of emissions per unit of GDP of 3% per year after 2020.
**Other Asia:** Several other Asian countries have pledged substantial emission reductions relative to baseline—most notably, South Korea (30% relative to baseline) and Indonesia (26% relative to baseline). As a group, we assume other Asian countries to deliver emission reductions of -20% relative to baseline by 2020. After 2020, they are assumed to decrease the emissions per unit of GDP by 3% per year, equal to the decarbonization rate assumed for China.

**Latin America:** Several other Latin American countries have pledged substantial emission reductions relative to baseline—most notably the Brazil (36% below baseline) and Mexico (30% baseline), which account for a substantial share of Latin American emission. We assume that Latin America as a group will deliver 10% emissions reduction from non-LUCF emissions. We further assume that LAM will reduce emissions intensity by 2.5% per year in 2020-2050 and 2050-2100.

**South Africa:** South Africa pledged a 34% reduction to baseline, but we assume that it will only deliver half of that. After 2020, emission intensities are reduced by 2.5% per year.

**Other Sub-Saharan Africa:** Africa is assumed not to take any targets before 2020. After 2020-50, a reduction target of emission intensity per unit GDP of 2% per year is prescribed. After 2050, a target on the reduction of emission intensity per unit GDP of 2.5% per year is assumed.

**South Korea:** 30% reduction from baseline in 2020 as pledged in the CA are assumed not to be reached, but 15% reduction will be achieved. Continued reductions of emission intensity of 3% per year after 2020, on par with those assumed for China.

**Other Asia:** Most of other Asia does not provide pledges, so we do not assume any reductions by 2020. After 2020, participation is ramped up to level of China, i.e. a reduction of emission intensity of 3% per year.

**Non-EU Eastern European countries and Turkey** are assumed to reach 15% emission reductions below baseline, similar to Korea, LAM and South Africa. Long-term reduction of emission intensity of 3% per year after 2020 is assumed.
Table SM1.2: Emission reduction targets for developing countries, excluding oil exporters. 2020 reductions are either formulated as reductions in the emission intensity of GDP (EI) or as reductions relative to baseline. These targets can be converted in yearly reduction rates \( gEI \) (rate of emission intensity reduction) or \( gEB \) (yearly emission reductions relative to baseline). After 2020, reduction rates have been considered in terms of \( gEI \) for all countries. Primary assumptions are highlighted in bold font.

<table>
<thead>
<tr>
<th>Percent reduction</th>
<th>2020 EI rel to 2005</th>
<th>2020 rel to baseline</th>
<th>( gEI \ [%/yr] ) / ( gEB )</th>
<th>( gEI \ [%/yr] ) 2020-50</th>
<th>2050 EI rel to 2020</th>
<th>( gEI \ [%/yr] ) 2050-2100</th>
<th>2100 EI rel to 2050</th>
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</thead>
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<td>-3%</td>
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<td>-3%</td>
<td>-78%</td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>-25%</td>
<td>-1.9% (gEI)</td>
<td>-3%</td>
<td>-60%</td>
<td>-3%</td>
<td>-78%</td>
<td></td>
</tr>
<tr>
<td>Brazil(^1)</td>
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<td>-0.7% (gEB)</td>
<td>-2.5%</td>
<td>-53%</td>
<td>-2.5%</td>
<td>-72%</td>
<td></td>
</tr>
<tr>
<td>Mexico(^2)</td>
<td>-10%</td>
<td>-0.7% (gEB)</td>
<td>-2.5%</td>
<td>-53%</td>
<td>-2.5%</td>
<td>-72%</td>
<td></td>
</tr>
<tr>
<td>Lat. America (LAM)</td>
<td>-10%</td>
<td>-1.1% (gEB)</td>
<td>-2.5%</td>
<td>-53%</td>
<td>-2.5%</td>
<td>-72%</td>
<td></td>
</tr>
<tr>
<td>South Korea(^2)</td>
<td>-15%</td>
<td>-1.1% (gEB)</td>
<td>-3%</td>
<td>-60%</td>
<td>-3%</td>
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</tr>
<tr>
<td>Other Asia</td>
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<td>-3%</td>
<td>-60%</td>
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</tr>
<tr>
<td>South Africa</td>
<td>-17%</td>
<td>-1.2% (gEB)</td>
<td>-2.5%</td>
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<td>-2.5%</td>
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<tr>
<td>Other Africa</td>
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<td>-45%</td>
<td>-2.5%</td>
<td>-72%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-EU Eastern Europe + Turkey(^3)</td>
<td>-15%</td>
<td>-1.1% (gEB)</td>
<td>-3%</td>
<td>-60%</td>
<td>-3%</td>
<td>-78%</td>
<td></td>
</tr>
</tbody>
</table>
Emission targets for resource exporters

The resource exporting regions of the Middle East and Former Soviet Union are assumed not to have an incentive to take any binding target. Countries of the Middle East have not pledged any emission reduction targets. Russia’s unconditional target of -15% below 1990 is well above projected baseline emissions. Carbon leakage, i.e. higher emissions compared to baseline in Group III countries in response to climate policies in Group I and II countries is allowed.

Emission control in Sectors

We assume all Kyoto-Gas Emissions excluding land use, land use change and forestry (LULUCF) to be included in the reduction targets and subject to climate policies. Given higher institutional requirements for monitoring and reporting of land-use related CO₂ emissions, we assume climate policies to be ineffective in controlling LULUCF emissions. LULUCF emissions are thus assumed not to be subject to carbon pricing, and are not included in the emission reduction targets.

International Emissions Trading

In the Weak Policy Scenario, we assume global carbon markets to remain fragmented. Specifically, the following rules for the trade of emission allowances and intertemporal flexibility in the mitigation effort were assumed to apply:

- No emissions trading, nor banking or borrowing is permitted until 2020
- After 2020, unrestricted emissions trading between members of Group I
- After 2020, unrestricted emissions trading between members of Group II
- The total net import of Group I (from Group II) is restricted to 20% of the combined mitigation requirement of Group I (i.e., the difference between baseline emissions and emission allowances under the cap).
- Full when-flexibility is allowed within the periods 2020-2050 and 2050-2100.
- Excess emission allowances from 2020-2050 can be banked to the 2050-2100 period, but no borrowing from the second period is allowed in the first period.
SM2: Carbon Prices in the Weak Policy scenario

Figure SM2.1 shows carbon price in the USA (member of Group I) and China (member of Group II) emerging in the three models for the WEAK-POL scenario.

Figure SM2.1: CO₂ price paths in the USA and China for the WEAK-POL scenario.
SM3: Regional GHG emissions

Figure SM3.1 shows GHG emissions budgets by region groups. GR1, GR2 and GR3 refer to the three region groups introduced in SM1.

(a) Cumulated GHG emissions (2005-2050) (b) Cumulated GHG emissions (2005-2100)

Figure SM3.1: Cumulated CO₂ emission trajectories for the baseline, WEAK-POL, WEAK-2020, WEAK-2030, and IMMEDIATE policy scenarios broken down by region groups.
SM4: Energy system

Figure SM4.1 and SM4.2 show the development of primary energy supply in the WEAK-POL, WEAK-2020 and WEAK-2030 scenarios. Figure SM3.3 depicts the differences between the WEAK-2020 and WEAK-2030 scenarios relative to IMMEDIATE.

Figure SM4.1: Global primary energy supply by carrier in the WEAK-POL scenario, and differences to BASELINE.
Figure SM 4.2: Primary energy supply in the WEAK-2020 scenario (left), and difference in global total to IMMEDIATE (right). Positive values indicate higher deployment in the WEAK scenarios. Note: these graphs are presented in different scales.
Figure SM4.3: Primary energy supply in the WEAK-2030 scenario (left), and difference in global total to IMMEDIATE (right). Positive values indicate higher deployment in the WEAK scenarios.
SM5: Premature retirement of fossil capacities

This section provides more detail on the results regarding pre-mature retirement of fossil capacities. Currently, about 90% of global primary energy supply comes from coal, oil and gas. Consequently, the fossil fuels account for the largest share of total installed capacity. Climate policy and pricing of CO₂ emissions are likely to make some of the fossil installations unprofitable, thus resulting in pre-mature retirement of fossil capacities before the end of their technical lifetimes. We explore to what degree weak near-term climate policy followed by an unanticipated future increase in climate policy stringency increases stranded fossil-based investments for electricity generation.

Figure SM5.1: Development of idle fossil capacities over time (a) globally aggregated, and in (b) Group I, (c) Group II, and (d) Group III countries.
Figure SM5.1 depicts the development of idle fossil capacities over time for the various scenarios, as well as a breakdown of cumulative idle capacities by fossil energy carrier. Already for the least cost pathway towards the 450 ppm CO₂e stabilization target (IMMEDIATE scenarios) a sizable share of pre-existing fossil capacities become unused. By 2030, between 600 (WITCH) and 1400 (GCAM) GW of fossil power generation capacity in are idle. This compares to a global total installed capacity of about 2000 GW in 2005. Early retirements peak later and at a higher level in the WEAK-2020 and WEAK-2030. In WITCH and REMIND, the maximum unused capacity in WEAK-2030 exceeds that of the IMMEDIATE scenario by more than a factor of two. There are two reasons for the increase in stranded capacities in the weak action scenarios. On the one hand, carbon prices in the near term action are insufficient to discourage further investments into fossil capacities, and the future increase in climate policy stringency is not anticipated. As a consequence fossil capacities at the time of target adoption are on a higher level than in the IMMEDIATE scenario. On the other hand, carbon prices after the target adoption are higher than in the IMMEDIATE Scenario, giving rise to higher pressure on the operators of carbon emitting installations.

In GCAM and REMIND, coal and gas plants become unused to a similar extent (Figure SM5.2). In WITCH, coal accounts for most of the stranded investments, mirroring the larger share of coal in electricity production. Stranded investments are unevenly distributed across regions. Initially, most of the retirements occur in industrialized countries. After 2025, by contrast, the emerging economies account for most of the idle capacities. China alone accounts for between 45 and 77% of the peak retirement.
Chapter 4

Carbon Lock-In through Capital Stock Inertia associated with Weak Near-Term Climate Policies

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Nils Johnson
Gunnar Luderer
Keywan Riahi
Morna Isaac
Jiyong Eom

Carbon lock-in through capital stock inertia associated with weak near-term climate policies

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1. Introduction

In the last four climate conferences in Copenhagen, Cancún, Durban and Doha, the international community has agreed on the target of limiting the increase in global average temperature to 2 °C above pre-industrial levels, while noting the “significant gap between the aggregate effect of Parties’ mitigation pledges […] and aggregate emission pathways consistent with having a likely chance of holding the increase in global average temperature below 2 °C or 1.5 °C [1,2]. While the discrepancy between mitigation pledges and required near-term emission levels implied by cost-optimal mitigation pathways towards 2 °C is well founded on previous research [3,4], the exact implications of higher-than-optimal emissions in the near term are less well explored. In an effort to inform societies and policy makers of the implications of proposed near-term mitigation pledges, the AMPERE study [5], on which this paper is based, examines the consequences of scenarios with different global emission levels in 2030, which correspond with current 2020 pledges extrapolated to 2030.
[6,7]. Complementing the companion AMPERE papers that focus on mitigation costs and feasibility [3] and technology deployment sensitivities and regional implications [8], this paper explores the implications of different short-term emissions targets for the transformation of the global energy system.

Understanding the differences in energy system transformation pathways helps to explain the economic costs and feasibility of scenarios with higher near-term emissions. Additionally, it can indicate how excess costs can be alleviated, but also where real-world barriers not included in the models can lead to even higher costs than reported by the models. To examine energy system transformation, we use a set of results from nine global energy-economy models participating in the AMPERE project to explore: 1) path dependency that results from the inertia of energy systems with long-lived infrastructure and 2) the implications of larger near-term emissions for the timing and magnitude of future mitigation. As near-term emissions targets become less stringent (i.e., emissions increase), the deployment of fossil energy infrastructure with long lifetimes, such as coal-fired power plants, is expanded. This additional carbon-intensive infrastructure potentially represents a long-term emissions commitment or carbon lock-in, which can threaten the likelihood of meeting more stringent long-term climate objectives, such as the 2°C target. Reaching the long-term stabilization target typically requires premature retirement or retrofit with carbon capture and storage (CCS) once the policy regime is strengthened in 2030, without prior anticipation by economic agents. Both of these options result in significant additional system costs, either through the write-off of stranded investments or the installation of CCS infrastructure [9].

Moreover, the rate at which these options can be deployed may be limited by technological limitations, social acceptance, and the ability to ramp-up additional low-carbon energy capacities as a substitute. Thus, this capital inertia causes some degree of path dependency, which limits the degree to which emissions can deviate from their previous trajectory.

In addition, because of the long residence time of CO₂ in the atmosphere, climate stabilization requires the solution of a stock problem. Climate change in a given year is largely determined by the cumulative anthropogenic emissions. Therefore, achieving long-term climate objectives becomes more difficult as 2030 emissions increase as a result of two distinct processes: 1) carbon budget depletion: larger pre-2030 emissions consume a higher share of the available CO₂ emissions budget, so that post-2030 emissions must be smaller and 2) carbon lock-in: the larger annual emissions and more carbon- and energy-intensive capital stock in 2030 significantly increases the rate at which the energy system must be transformed and increases the cost of reaching a particular level of emission reductions relative to the previous trajectory.

For the remainder of this paper, we consequently refer to carbon lock-in as the degree to which the configuration of the energy system in 2030 is less than optimal, thus increasing the difficulty of emission reductions achieved post-2030. We do this being well aware that the models are only able to capture the restricted aspect of carbon lock-in associated with physical capital and emissions while institutional and other aspects of this phenomenon [10] are not modeled and hence not the subject of this study. Furthermore, currently existing energy infrastructure also constitutes a considerable emissions commitment and hence carbon lock-in today [11].

Our study thus explores how much this lock-in is increased by policies that institute only modest mitigation over the next two decades and what this lock-in implies for the long-term energy system transformation that is required for achieving a low stabilization target.

We present the modeling and scenario framework of this study in Section 2 and discuss the magnitude and composition of the lock-in attained in 2030 in Section 3. Section 4 discusses the long-term budget implications of both the carbon budget depletion and the lock-in from both temporal and sectoral perspectives and Section 5 concludes with a discussion of the results.

2. Study design and methods

This cross-cut analysis is part of the AMPERE model inter-comparison study, which examines mitigation timing and alternative technology futures and is described in detail in the overview article of this special issue [5]. A total of nine energy-economy and integrated assessment models participated in the study (Table 1). To improve comparability of results, model assumptions on regional GDP trajectories and global long-term final energy demand levels were harmonized for the baseline scenarios.

Table 2 provides an overview of the scenarios considered in this paper. They comprise a subset of the scenarios prepared for the AMPERE study [5] and are specifically designed to explore the two phenomena of carbon lock-in and carbon budget depletion explained in Section 1. The baseline scenarios ("Base") represent a future in which the energy system develops without climate policy while the climate mitigation scenarios ("450") must fulfill a constraint on cumulative CO₂ emissions, including land use emissions, from 2000 to 2100 of 1500 Gt CO₂ [5]. This is roughly consistent with a limitation of the atmospheric greenhouse gas (GHG) concentration to 450 ppm CO2e in 2100, and implies an about 60–70% likelihood of keeping temperature change relative to pre-industrial levels in 2100 below 2°C [12]. The analysis presented in this paper considers only scenarios in which the full portfolio of technologies represented in each model is available, both with reference energy intensity (FullTech) and lower energy intensity as a sensitivity analysis (LowEI). For the FullTech scenarios, the observed rate of energy intensity improvement of roughly 1.3% per year is assumed to be continued in the future, leading to a

---

1 Here we use the term carbon lock-in to describe how less-than-optimal climate policies result in an energy system configuration that is more emissions-intensive than implied by optimal climate policies. In contrast to Davis et al., we do not quantify the contribution of this excess fossil-based infrastructure to future emissions.

2 The model with temporal modeling scope until 2050 (DNE21+) has to fulfill a cumulative budget of 1500 Gt CO₂ in the period 2000–2050, which is broadly comparable to the emissions of the other models in that time span (see Section 4.1). For the two models that do not include land-use CO₂ emissions (IMACLIM and POLISSE), the budget is only 1400 Gt CO₂. Models considering further GHGs beyond CO₂ apply an equivalent price to those emissions, using global warming potentials (GWPs) for the price conversion.
global final energy demand of 910–1000 EJ in 2100 [5]. Higher energy intensity improvement rates of ~1.9% per year are assumed to happen autonomously without additional policies or costs in the LowEI scenarios, resulting in 520–570 EJ final energy demand in 2100. An in-depth analysis of scenarios with limited technological representation is presented in the companion cross-cut paper [8].

To study carbon lock-in, we consider scenarios with prescribed (typically sub-optimal) short-term mitigation targets in 2030, along with scenarios with full when-flexibility and an optimal distribution of emission reductions over time. The scenarios with prescribed 2030 targets were constructed as two-stage scenarios in models with perfect foresight, so that they run in myopic mode until 2030 with no anticipation of the post-2030 policy signal before 2030 (see Bosetti et al. [13] and Richels et al. [14] for a discussion with the opposite cases of anticipated policy changes). Specifically, the model considers

---

### Table 1

<table>
<thead>
<tr>
<th>Model name</th>
<th>DNE21+</th>
<th>GCAM</th>
<th>IAMCLIM</th>
<th>IMAGE</th>
<th>MESSAGE</th>
<th>POLES</th>
<th>REMIND</th>
<th>WITCH</th>
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</thead>
<tbody>
<tr>
<td>Short form</td>
<td>D</td>
<td>G</td>
<td>I</td>
<td>i</td>
<td>M</td>
<td>m</td>
<td>P</td>
<td>R</td>
</tr>
<tr>
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<td>2050</td>
<td>2100</td>
<td>2100</td>
<td>2100</td>
<td>2100</td>
<td>2100</td>
<td>2100</td>
<td>2100</td>
</tr>
<tr>
<td>Premature retirement</td>
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<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Max. primary energy biomass (EJ)</td>
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<td>880</td>
<td>278</td>
<td>266</td>
<td>189</td>
<td>221</td>
<td>211</td>
<td>306</td>
</tr>
</tbody>
</table>

### Table 2

Scenarios analyzed in this study. The codes in parentheses will be used throughout this study to refer to the scenarios. The 450-FullTech-LST and 450-FullTech-HST scenarios will be referred to in short as LST and HST respectively.

<table>
<thead>
<tr>
<th>No climate policy (Base)</th>
<th>Centennial CO2 emission budget constraint of 1500 Gt CO2 (450 ppm CO2e)</th>
<th>Low when-flexibility (OPT)</th>
<th>Low short term target (LST)</th>
<th>High short term target (HST)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference energy intensity (FullTech)</td>
<td>Base-FullTech-OPT</td>
<td>450-FullTech-OPT</td>
<td>450-FullTech-LST</td>
<td>450-FullTech-HST</td>
</tr>
<tr>
<td>Low energy intensity (LowEI)</td>
<td>Base-LowEI-OPT</td>
<td>450-LowEI-OPT</td>
<td>450-LowEI-LST</td>
<td>450-LowEI-HST</td>
</tr>
</tbody>
</table>

---

Fig. 1. Historic global CO2 emissions until 2010 and projected emissions until 2030 for the 450-FullTech-HST scenario based on the REMIND model. The bar plots on the right side indicate projected CO2 emissions in 2030 by the REMIND model for the four FullTech scenarios. The vertical black lines indicate the full range of total CO2 emissions across the nine models and the grey boxes the interquartile range. Historic data is from Refs. [17,20,21]. Definitions of variables can be found in the AMPERE database and derived variables are defined in the supporting online material.
two short-term targets: high ("HST") and low ("LST"). In the HST scenarios, the target for total Kyoto gas emissions in 2030 is 60.8 Gt CO$_2$e and in the LST scenarios the target is 52.8 Gt CO$_2$e in 2030. As seen in Fig. 1, the HST scenarios imply weaker-than-optimal mitigation efforts and hence policies until 2030. Therefore we refer to the HST scenarios as weak policy scenarios in relation to the OPT scenarios. However, the weak designation should only be understood in a relative sense and does not imply any absolute valuation of the considered policy targets.

The short-term targets were developed by extrapolating the 2020 pledges under the UNFCCC to 2030 and reflect likely emissions outcomes for stringent fulfillment of those pledges (IST) and a more lenient case (HST) where only unconditional pledges are fulfilled [5]. For most models, the two targets lie within the range spanned by the baseline scenario on the high end and the optimal 450 scenario on the low end, although there is an overlap between optimal scenarios and those with low short term targets (see bars on the right side of Fig. 1). The left side of Fig. 1 compares the trajectory of historic CO$_2$ emissions with the trajectory projected until 2030 by REMIND for the 450-FullTech-HST scenario. Although the HST scenario represents the highest 2030 CO$_2$ emissions of any of the 450 ppm mitigation scenarios and, thus, the most carbon budget depletion and lock-in, it still implies significantly lower emission growth rates than those observed in the last decade. The IST scenario represents an intermediate level of carbon lock-in and roughly implies a return to current emission levels by 2030. Finally, in the first best climate policy scenario (450-FullTech-OPT), 2030 emissions are considerably lower than those in 2010 for the majority of models. The difference in emissions between the HST and the 450-OPT scenario is roughly 15 Gt CO$_2$ for most models, or close to 50% of total 2010 emissions.

3. Energy System in 2030: Which sectors contribute most to carbon lock-in?

This section evaluates carbon lock-in and its main contributors for scenarios with sub-optimal short-term emission targets (IST and HST). Specifically, the sectors...
that contribute most to carbon lock-in are identified by calculating the difference in energy system deployment and CO2 emissions relative to 450-OPT scenarios for each sector in 2030, which is when the near-term target is specified and the myopic period ends.

While total 2030 emissions are exogenously prescribed via the short-term target definitions in the HST and LST scenarios, the sectoral composition of the emissions is an endogenous model outcome. By contrast, 2030 emissions in the OPT scenarios are determined endogenously in each model. Consequently, the overall size and composition of the CO2 emissions gap between the HST and 450-OPT scenarios shown in Fig. 2a vary across models. While GCAM identifies a very small gap of less than 1 Gt CO2, the range across the rest of the models is 8–24 Gt CO2, which is comparable to 21–65% of total global CO2 emissions in 2010. Most models indicate that more than half of the foregone emissions abatement is attributed to the electricity supply. Generally, the second largest contribution comes from additional demand-side emissions from the consumption of combustible fuels.

As expected, the lesser ambitious emission reductions in the HST scenario are caused by greater deployment of fossil primary energy without carbon capture and sequestration (CCS) relative to the OPT scenario (Fig. 2b). The increase in fossil primary energy demand amounts to 90–270 EJ, which compares to 431 EJ of fossil energy use observed in 2010. Within the group of fossil fuels, coal exhibits the largest increase in deployment. Furthermore, we observe less deployment of low-carbon energy sources and a substantial net increase of primary energy of 50–200 EJ.

Increased fossil fuel use is also evident in the electricity sector where significantly more electricity is generated using coal and gas plants without CCS in the HST scenario (Fig. 3a). Coal-based electricity generation increases up to 17 PWh or 60 EJ, compared to total global electricity generation of 21 PWh or 77 EJ in 2010. In addition, low-carbon generation technologies, such as coal and gas with CCS, nuclear, biomass and other renewables, are deployed at lower levels. Consequently, the
price of electricity is smaller in the HST scenario until 2030, resulting in a greater net demand for electricity. The increase in electricity generation with fossil fuels generates much of the surplus emissions until 2030 and the underinvestment into low-carbon options leads to higher ramp-up rate requirements for these options after 2030, particularly in the two subsequent decades [8].

Regarding differences in final energy use by carrier, it is noteworthy to observe that electricity makes up only a small portion of the additional final energy use relative to the OPT scenario (Fig. 3b). The HST scenario tends to yield lower price-induced energy efficiency improvements until 2030, resulting in a difference in total final energy use compared to OPT of up to one third of 2010 total final energy use.

Figs. 2 and 3 suggest that the difference in emissions abatement in the year 2030 between the HST and OPT scenario is primarily the result of two processes: 1) end-use efficiency improvements are higher in the OPT scenarios than in the HST scenarios and in most models the difference is evenly distributed across the different end-use fuel types; and 2) the carbon intensity of electricity supply is much further reduced in the OPT scenario than in the HST scenario, whereas the carbon intensity of non-electric final energy supply is not significantly lowered in comparison to the baseline even in the OPT scenario (Fig. 4). This pattern reflects the greater difficulty and cost of emissions reductions in non-electric energy supply [15,16] and the comparatively low marginal abatement costs for many efficiency measures and the substitution of coal-based electricity generation with low-carbon alternatives.

The substitution of low-carbon alternatives for coal is comparatively cheap because new generation capacities must be built anyway, given the projected rise in electricity demand across the world. In the optimal policy scenario, all models foresee stagnation or even a net decline in installed capacity for coal-based electricity generation without CCS in 2030 relative to 2010. By contrast, the HST scenario implies a net increase of these capacities in most models (Fig. 5a). Even if the total capacity stagnates for the next two decades, significant new capacity will still be required to replace retired facilities. Since coal power plants are characterized by long technical lifetimes, typically ranging from 30 to 50 years, any new capacity built over the next two decades will contribute to significant lock-in of carbon intensive generation. In the HST climate mitigation scenarios in which the electricity sector must rapidly decarbonize after 2030, most models, must prematurely retire and thus strand large amounts of this coal capacity (Fig. 5b).

Johnson et al. [9] discusses the costs and implications of stranded coal capacity given various near-term emissions targets.

In the LowEL scenarios, total installed coal capacities under short-term targets are very similar to those found in the reference energy intensity (FullTech) scenarios even though overall final energy demand is much smaller (Fig. 5a). This means that the end-use efficiency improvements, which are assumed to happen autonomously (i.e. without any costs involved), in these scenarios, reduce the urgency of transitioning to low-carbon electricity generation. Consequently, the carbon intensity of electricity is higher in the LowEL HST and LST scenarios than in the corresponding FullTech scenarios (Fig. 4a). While in general it is a trivial result that with fixed emission targets, scenarios with less energy demand yield higher carbon intensities, it is noteworthy that coal-based electricity generation, which involves very long-lived capital stocks, is nearly identical in the LowEL and FullTech scenarios.

The main insight from the analysis in this section is that the majority of foregone abatement options in the LST and HST scenarios are reductions in coal-based electricity production. As the corresponding production capacities represent long-lived capital assets, the expansion of coal constitutes a considerable lock-in of carbon-intensive technologies. Meanwhile, reduced investment in low-carbon technologies means that the share of these technologies remains low in 2030. In combination, these developments pose a considerable challenge for the rapid transition to low-carbon energy that is required in the following decades to limit warming to 2 °C.

![Fig. 4. Carbon intensity of secondary energy electricity (left panel) and final energy without electricity (right panel) in 2030 for all eight scenarios. The red lines mark the median level across all models, the colored boxes indicate the interquartile ranges and the whiskers indicate the full model ranges. The letters indicate the values associated with each model (see Table 1 for full model names). The dashed horizontal line marks the 2010 historic value [22].](image-url)
4. The effects of short-term emission targets on long-term emission patterns

This section discusses the temporal and sectoral allocations of the allowable CO₂ budget in scenarios with optimal versus weak near-term policies and describes the differences in these allocations among models.

4.1. Exhausting the emissions budget

Achieving stringent long-term climate protection targets requires that cumulative emissions of CO₂ are strictly limited. In the 450 ppm scenarios considered in this study, less than 1200 Gt CO₂ can still be emitted between 2010 and 2100, as more than 300 Gt have been emitted from 2000 to 2009 [17]. For comparison, more than 1600 Gt CO₂ of anthropogenic emissions have been emitted in the 90 years between 1920 and 2009. Even under the assumption of immediate action as in the 450-OPt scenario, more than half of the 2010–2100 budget will be consumed within the next two decades, which leaves only 400–550 Gt CO₂ for the period from 2030 to 2100 (Fig. 6). As emissions until 2030 are even larger in the HST scenario, the budget for the remaining seven decades of the 21st century would be reduced to 320–410 Gt CO₂, thus increasing the challenge significantly.

The magnitude of the challenge becomes evident when one examines the cumulative emissions in 2050 for both scenarios. In the 450-OPt scenario, roughly half the models already exhibit an overshoot over the allowable CO₂ emissions budget in 2050, making the achievement of the long-term budget dependent on successful removal of considerable amounts of CO₂ in the second half of the century. For all but one model, cumulative emissions until 2050 are considerably larger in the HST scenario, which increases the need for carbon dioxide removal (CDR) from the atmosphere and thus increases the risk of failing to meet the long-term target, as reflected in the infeasibility of this scenario in two of the nine models. In the HST scenario, the models with time horizons to 2100 cluster into two distinct groups based on how much they overshoot the long-term budget in 2050. Four models (GCAM, MESSAGE, MERGE-ETL and REMIND) substantially overshoot the budget by more than 200 Gt CO₂ in 2050, while two models (POLES and WITCH) are roughly at the maximum budget level in 2050 and overshoot the budget only modestly in later decades. This grouping coincides with the tentative model classification scheme described by Kriegler et al. [18], as all models belonging to the "high response" group show a high overshoot. Models in these groups generally are more sensitive to carbon prices, reduce carbon intensity more quickly than energy intensity and can more rapidly transform the energy system.

4.2. Sectoral and temporal composition of the CO₂ emissions budget in scenarios with optimal and weak near-term policies

From the analysis of emissions budgets it becomes clear that the differences between mitigation pathways with weak near-term action and optimal pathways can be characterized in terms of three distinct temporal phases: (i) a carbon lock-in phase during the weak policy regime from 2010 to 2030; (ii) a catch-up phase from 2030 until about 2050 characterized by very high decarbonization rates; and (iii) a compensation...
phase after 2050, during which excess emissions in the first half of the century are compensated by emission levels below those observed in the OPT scenario. Differences in the temporal allocation of emissions also influence their sectoral allocation and can be related to the three temporal phases. Currently nearly half of global CO2 emissions from the energy sector originate from transformation processes on the supply side of the energy system, mainly electricity generation (Fig. 1). Previous studies on ambitious mitigation have pointed out that supply side emissions are more easily mitigated so that the supply share of emissions decreases in mitigation scenarios [15,16] and can even turn negative. In scenarios with weak near-term policy (HST and LST), the share of emissions from the supply side does not decrease much by 2030 (Fig. 1), and thus, much of the excess emissions in comparison to optimal near-term scenarios (OPT) during the 2010–2030 period comes from the supply side (Fig. 7).

During the 2030–2050 period, the change in emissions between the OPT and HST scenarios is not consistent among models. While some models (WITCH, MERGE-ETL, and DNE21+) achieve lower emissions, at least in some sectors, in the HST scenario, other models (REMIND, POLES, and MESSAGE) have excess emissions in all sectors in the 2030–2050 period that are similar to those in the 2010–2030 period (Fig. 7). For DNE21+, this is directly linked to its 2050 time horizon and the scenario definition, which mandates the same cumulative emissions over the 2010–2050 period in both the OPT and HST scenarios.

For models with time horizons to 2100, the amount of CO2 emitted during the 2030–2050 period in the weak policy scenarios can be explained by two factors: 1) path dependency during the transition to a more stringent climate policy regime, and 2) the long-term emissions abatement potential. Models with strong path dependency are less flexible in the rate of emission reductions achieved in the short-term. Both factors are influenced by energy system characteristics on both the supply and demand sides (see Table 1). On the demand side, a model's path dependency is determined by a model's short-term price elasticity of energy service demand and the ability to ramp-up low-carbon demand technologies (e.g., biofuels, solar heating and electro mobility). On the supply side, a model's ability to reduce emissions is constrained by the ramp-up potential of low-carbon supply options like nuclear, bioenergy, wind and solar [8] and the ability to prematurely retire carbon-intensive fossil-based generation capacity. Similarly, the long-term emissions abatement potential is determined by assumptions about sectoral energy demands and their long-term efficiency potentials, low-carbon energy supply options, and the availability of technologies to remove CO2 from the atmosphere, such as bioenergy with carbon capture and storage (BioCCS).

Models with high path dependency and/or high long-term mitigation potential tend to have higher 2030–2050 emissions, while models with lower long-term mitigation potentials need to perform deeper emission reductions in the 2030–2050 period. Since carbon prices reflect the marginal costs of mitigation in each time period, the prices in 2050 can serve as proxies for the difficulty and/or necessity of mitigating CO2 from 2030 to 2050. As the short-term 2030 target increases, the need for mitigation generally increases for the 2030–2050 period and, thus, the 2050 carbon price also increases (Fig. 8). However, there is significant variation in the carbon price among the models with two distinct clusters evident in the HST
scenario: those with relatively high carbon prices and those with low prices. The models with high absolute carbon prices in 2050 include MERGE-ETL, WITCH and POLES. The high prices suggest that the energy systems in these models are pushed close to the limits of their mitigation potentials. However, the reasons why these models are pushed to their mitigation limits by 2050 differ.

For MERGE-ETL, the model has difficulty reducing emissions in this period, particularly in the electricity sector where no premature retirement of built capacities is possible. As a result, the model significantly overshoots the long-term budget in 2050 and compensates with net negative emissions in the latter half of the century (Fig. 6 and Fig. A1 in the supplementary online material). By contrast, POLES and WITCH cannot achieve large net negative emissions in the long-term and, thus, cannot significantly overshoot the long-term budget in 2050 and still meet the long-term target (Fig. 6 and Fig. A1). As a result, these models must put much more effort into decreasing emissions in the 2030–2050 period, resulting in more mitigation and a larger increase in carbon prices. The models with more modest carbon prices include MESSAGE, REMIND, and GCAM. These models include a large variety of low-carbon energy supply options and achieve large net negative emissions in the latter half of the century and, thus, they can significantly overshoot the long-term budget in 2050 (Fig. A1).

In the second half of the century, all models that found the HST scenario feasible achieve either net negative or zero cumulative emissions during this period using primarily biomass with CCS (BioCCS) (Fig. A1). Furthermore, in the HST scenario, all models, except GCAM, reduce cumulative emissions by an additional 100–250 Gt CO₂ relative to the OPT scenario to compensate for excess emissions up to 2050 (Fig. 7). Most of the additional reduction comes from the demand sector, with relatively smaller contributions from the decrease of positive supply emissions and increase of negative supply emissions associated with BioCCS. This finding suggests that most of the BioCCS potential is utilized in both the OPT and HST scenarios so the additional emissions reductions required in the HST scenario largely come from reduced energy demand. Two models (WITCH and POLES) have quite substantial cumulative positive supply side emissions of 150–230 Gt CO₂ in the 450-OPT scenario that decrease by less than 15% despite the roughly doubled CO₂ price in the HST scenario (Fig. A1). This finding suggests that WITCH and POLES cannot decarbonize the energy supply as much as other models. Consequently, despite significant CO₂ removal potential, negative emissions are only sufficient to balance positive emissions and large net negative emissions are not achieved by these models.

In summary, this section indicates that if models are to achieve the long-term climate target in the HST scenario, they must have either the ability to achieve large net negative emissions in the latter half of the century or the ability to rapidly transition to low-carbon energy technologies and achieve net zero emissions in the latter half of the century. In scenarios with lower energy intensity (LowEI) these requirements are less severe as the lower baseline final energy demand provides the models with more flexibility and less urgency in addressing long-term mitigation. This means that not only can investments in low carbon technologies be stretched out over longer periods of time, but also the phase-out of carbon-intensive technologies can be more gradual. For example, less coal-based electricity generation capacity is stranded in the LowEI scenarios (Fig. 5b). As a result, the mitigation costs and carbon prices in LowEI scenarios are much lower than in scenarios with reference energy intensity (Fig. 8). For all models with time horizons until 2100, it is less expensive to achieve the cumulative budget with low energy intensity after two decades of weak climate policy (450-LowEI-HST) than it is in the scenario with immediate mitigation and reference energy intensity (450-FullTech-OPT).
This is especially noteworthy, as the carbon lock-in in 2030 is very similar in the low and reference energy intensity scenarios in 2030 (Section 3 and especially Fig. 5a).

5. Discussion

This study provides several policy-relevant insights into the implications of weak near-term policies on the achievability of long-term climate targets, such as the 2 °C target. Under these policies, all models indicate that most of the foregone near-term abatement results from increases in coal-fired electricity generation. Consequently, if global warming is to be limited to 2 °C in 2100, the models indicate that huge quantities of installed coal capacity will need to be prematurely retired between 2030 and 2050. Such a vast global write-off of capital would be unprecedented in scale. Even though early retirement avoids extra emissions of up to 200 Gt CO₂, weak policy scenarios essentially guarantee that the long-term cumulative budget will be exceeded around 2050. Therefore, another insight is the necessity of achieving significant negative emissions in the second half of the century using biomass with CCS and terrestrial sequestration. As near-term emissions targets become less stringent (i.e., as action is delayed), the magnitude of required negative emissions increases, which poses a larger risk of failure in meeting long-term climate objectives.

The results also imply that concerted efforts to improve energy efficiency will not prevent lock-in of coal-based electricity capacity, at least if weak near-term policies are implemented as emission targets. Rather, low energy demand coupled with emission targets reduces pressure to decrease carbon intensity on the supply side and, thus, allows the share of fossil energy to increase in the near-term. However, in the longer term, this reduced pressure is also beneficial because it increases the flexibility of the energy system in making a transition that is consistent with a 2 °C target. Furthermore, the additional flexibility and reduced investment on the supply side reduce carbon prices and mitigation costs, which improve the economic feasibility of achieving the climate objective.

The comparison of model results also suggests that further research is needed to explore the uncertainties regarding key assumptions in the models. In particular, while all results are subject to the general limitations of long-term energy-economic modeling, it is noteworthy that the feasibility and costs of sub-optimal near-term policy scenarios are strongly dependent on assumptions regarding the availability and cost of carbon dioxide removal in the second half of the century [8]. In addition, assumptions regarding premature retirement and the availability and relative costs of electricity supply technologies influence the ability of models to swiftly decarbonize the electricity sector and cope with large write-offs of stranded capital in the resource extraction (see also Ref. [19]) and fossil fuel sectors. Furthermore, most models do not account for potential political and other non-economic barriers to both stranding significant electricity capacity and rapidly ramping up low-carbon technologies. Thus, the models may overestimate how rapidly an energy system transition can occur. For this reason, further research is needed to explore the risks and uncertainties associated with achieving rapid energy system transformations and large net negative emissions.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.techfore.2013.10.001.
References


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Supplementary Online Material

*Carbon lock-in through capital stock inertia associated with weak near-term climate policies*

Christoph Bertram, Nils Johnson, Gunnar Luderer, Keywan Riahi, Morna Isaac, Jiyong Eom

A Definitions of derived variables

Table 1: Primary Variables from AMPERE database used for calculations

<table>
<thead>
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<th>Primary Variables</th>
<th>Symbol</th>
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Table 2: Derived variables and calculation formula

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<td>...Energy Supply</td>
<td>Electricity</td>
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<td>...Energy Supply</td>
<td>Other</td>
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<td>Other</td>
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<tr>
<td>Carbon Intensity of Electricity</td>
<td>$C_{el}$</td>
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</table>
Carbon Intensity of other Final Energy

\[ CI_{oth} = \frac{Em_{FFI} - Em_{GS-el}}{SE_{el}} \]

Energy Intensity

\[ EI = \frac{FE}{GDP_{MER}} \]

Carbon Intensity

\[ CI = \frac{Em_{FFI}}{FE} \]

Idle Coal Capacity

\[ Idle_{Coal}^{pol} = C_{Pol} \left( \frac{SE_{Base}^{Coal} - S/A}{C_{Pol}^{Base} + S/A} - \frac{SE_{Pol}^{Coal}}{C_{Pol} + S/A} \right) \]

Increase in Mitigation Cost

\[ \Delta MitCost_{\text{scen}} = \frac{\sum_{2100}^{2100}(0.95(\text{year} - 2005) \times PC_{X_{\text{scen}}})}{\sum_{2100}^{2100}(0.95(\text{year} - 2005) \times PC_{450-FullTech-OPT})} - 1 \]

B Supplementary Figures

Figure A1: Cumulative CO₂ emissions for 450-FullTech-OPT and 450-FullTech-HST for three periods: 2010-2030, 2030-2050 and 2050-2100. The initials on the right side indicate the model names (see Table 1 for full names) and the black diamonds represent net emissions. GCAM shows more than double the negative emissions of other models, with roughly 20% from non-BioCCS technologies (bioplastics, terrestrial sequestration).

\[ ^{1} \text{As not all models can report all different policy cost metrics, the metric used differs across models. Therefore, in Figure 8 we look at the ratios of these policy costs between scenarios. The first reported policy cost metric } PC_{X} \text{ is used for each model, following the order } PC_{MAC}, PC_{CL}, PC_{ESC}, \text{ and } PC_{GL}. \]
Figure A2: Differences in other secondary energy types by carrier and source between 450-FullTech-HST and 450-FullTech-OPT in 2030.

a)

b)
Figure A3: Differences in a) CO₂ emissions by sources, b) primary energy types, c) secondary energy electricity generation, d) other secondary energy and e) final energy by carrier between 450-LowEI-HST and 450-LowEI-OPT in 2030. Dashed line indicate reference values in 2010 [24].
Figure A4: Medians of cumulative CO₂ emissions after 2010 (red lines) across models together with interquartile ranges (grey boxes) and full model ranges (whiskers) for four points in time and two scenarios. The colored boxes illustrate the differences between medians from one time step to the next (please note that they do not represent the medians across models of the emission budgets in those periods). The dark grey box on the left side represents total CO₂ emissions from fossil fuels, industry and land-use from 1920-2009 [19,22,23]. The dotted horizontal line marks the 2100 emissions budget target.

Figure A5: Differences in cumulative sectoral CO₂ emissions between the 450-LowEI-OPT and 450-LowEI-HST scenarios for all models and three time periods: 2010-2030, 2030-2050 and 2050-2100. For IMACLIM, the 450-LowEI-HST scenario was infeasible.
Figure A6: Cumulative CO₂ emissions for 450-LowEI-OPT and 450-LowEI-HST for three periods: 2010-2030, 2030-2050 and 2050-2100. The initials on the right side indicate the model names (see Table 1 for full names) and the black diamonds represent net emissions. For IMACLIM, the 450-LowEI-HST scenario was infeasible.
Chapter 5

Long-term Climate Policy Implications of Phasing Out Fossil Fuel Subsidies

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Long-term climate policy implications of phasing out fossil fuel subsidies

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**HIGHLIGHTS**
- We assess implications of phasing out fossil fuel subsidies on the mitigation of climate change.
- The removal of subsidies leads to a net-reduction in the use of energy.
- Emission reductions contribute little to stabilize greenhouse gases at 450 ppm if not combined with climate policies.
- Low carbon alternatives may encounter comparative disadvantages due to relative price changes at world markets.

**ABSTRACT**
It is often argued that fossil fuel subsidies hamper the transition towards a sustainable energy supply as they incentivize wasteful consumption. We assess implications of a subsidy phase-out for the mitigation of climate change and the low-carbon transformation of the energy system, using the global energy–economy model REMIND. We compare our results with those obtained by the International Energy Agency (based on the World Energy Model) and by the Organization for Economic Co-Operation and Development (OECD-Model ENV-Linkages), providing the long-term perspective of an intertemporal optimization model. The results are analyzed in the two dimensions of subsidy phase-out and climate policy scenarios. We confirm short-term benefits of phasing-out fossil fuel subsidies as found in prior studies. However, these benefits are only sustained to a small extent in the long term, if dedicated climate policies are weak or nonexistent. Most remarkably we find that a removal of fossil fuel subsidies, if not complemented by other policies, can slow down a global transition towards a renewable based energy system. The reason is that world market prices for fossil fuels may drop due to a removal of subsidies. Thus, low carbon alternatives would encounter comparative disadvantages.

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1. Introduction

In 2009, G20 leaders committed to “rationalize and phase-out over the medium term inefficient fossil fuel subsidies that encourage wasteful consumption” (G20, 2011). Despite this commitment, subsidies to fossil fuels continue to grow reaching about 523 billion USD in 2011 (WEO, 2012). Motivations for these governmental expenditures range from energy security concerns to supporting domestic production and job markets, alleviating energy poverty, and redistributing wealth (Porter, 2020; Koplów et al., 2010; WEO, 2010; del Granado et al., 2012; OECD, 2012). However, by distorting markets and discouraging the production and use of clean energies, fossil fuel subsidies do not only cause economic inefficiencies but they may also hamper a transition towards a sustainable provision of energy.

In this paper, we aim to answer two questions: (1) To what extent can a phase-out of fossil fuel subsidies pave the road towards the stabilization of greenhouse gas emissions? (2) To what extent can a phase-out of fossil fuel subsidies trigger a transition of the energy system towards a clean and sustainable provision of energy? We answer these questions by analyzing scenarios that span two policy dimensions – a varying degree of phasing out fossil fuel subsidies in combination with varying degrees of climate stabilization policies.

Due to the difficulty in identifying, collecting, and measuring fossil fuel subsidy data, attempts to quantify global benefits from phasing out fossil fuel subsidies were made only recently. A milestone is the database published by the International Energy Agency (2013), which includes data for consumer subsidies in 37 countries for coal, natural gas, oil, and electricity. This large data set can be used to study scenarios for the phase-out of fossil fuel subsidies with the help of integrated assessment models. Currently, two models have provided an analysis of such scenarios. The first model is the OECD’s world general equilibrium model ENV-Linkages that has provided the background analysis for the

There are large and partly intrinsic uncertainties inherent in modelling the global energy–economy system and its inter-linkages with the climate system. These circumstances strongly suggest to compare results across a variety of models instead of looking at single model results only. Thereby, the confidence into the robustness of result can be strengthened. This is even more important as this class of models cannot be validated (Oreskes et al., 1994). Using the integrated assessment model REMIND, we study the impacts of phasing out fossil fuel subsidies in light of an intertemporal energy–economy model with perfect foresight (Leimbach et al., 2010; Luderer et al., 2012a,b; Bauer et al., 2012).

The structure of this paper is as follows. In Section 2 we compare the model frameworks of REMIND, ENV-Linkages, and the World Energy Model and we describe our scenario set-up for the mitigation of climate change and a low-carbon transition of the energy system. Finally, we conclude, linking the results of our study to current policy initiatives.

## 2. Comparison of modelling frameworks and scenario set-up

### 2.1. REMIND compared to ENV-Linkages and the World Energy Model

The global energy–economy system with linkages to the climate system is a complex system involving large uncertainties. These uncertainties do not only lie in historical data, interpretations of past and present developments, or limited knowledge of the best level of spatial and sectoral coverage. But uncertainties also concern fundamental laws governing the development of the socio-economic system. Therefore, and due to computational limitations, modelling teams have to make a multitude of choices and assumptions when modelling the global energy–economy system, refer e.g. to van Vuuren (2009) for a concise overview about challenges and different modelling approaches.

Here we provide an analysis of the effects of phasing out fossil fuel subsidies based on the REMIND model. This model uses a different modelling approach than ENV-Linkages and the World Energy Model, refer to Table 1 as a basis for the comparison. A key difference is the assumption of myopic behaviour in the World Energy Model and in ENV-Linkages, whereas REMIND features perfect foresight. Furthermore, model objectives are distinguished in the following: ENV-Linkages is set-up to maximize producer profits and consumer welfare in a recursive-dynamic mode. The World Energy Model follows a least-cost approach to satisfy energy service demand. REMIND’s objective is to maximize intertemporal welfare at the global level. It should also be pointed out that only in REMIND prices develop endogenously, determined by short- and long-term scarcities.

### 2.2. Data basis for fossil fuel subsidies

Fossil fuel subsidies come in different types targeting consumers and/or producers. They occur, e.g. as direct financial transfers, tax credits or tax exemptions, trade restrictions, reduced prices for energy-related services, or governmental interventions in the energy market. The consequence of fossil fuel

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Table 1

<table>
<thead>
<tr>
<th>Feature</th>
<th>ENV-Linkages</th>
<th>World Energy Model</th>
<th>REMIND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional coverage</td>
<td>12 regions</td>
<td>25 regions</td>
<td>11 regions</td>
</tr>
<tr>
<td>Sectoral coverage</td>
<td>25 economic sectors</td>
<td>15 economic sectors</td>
<td>10 final energy types</td>
</tr>
<tr>
<td>Type of model</td>
<td>Recursive-dynamic computable general equilibrium, myopic agents, some trend projections</td>
<td>Simulation of energy markets, no foresight apart from trend projections</td>
<td>Inter-temporal optimization, perfect foresight</td>
</tr>
<tr>
<td>Model objective</td>
<td>Static maximization of producer profit and consumer welfare</td>
<td>Least-cost approach to meet energy service demand</td>
<td>Dynamic max. of global welfare, Pareto-optimum among regions</td>
</tr>
<tr>
<td>Population</td>
<td>UN 2006/2008, medium project</td>
<td>UN 2010, medium projections</td>
<td>UN 2010, medium projections</td>
</tr>
<tr>
<td>Global GDP growth</td>
<td>3.5% (2005–2050)</td>
<td>3.5% (2010–2035)</td>
<td>3.9% (2010–2035), 3.5% (2005–2050)</td>
</tr>
<tr>
<td>Final energy demand</td>
<td>Based on existing energy infrastructure, demand met by the least cost approach, AEE tuned to meet WEO</td>
<td>Based on existing energy infrastructure, demand met by the least-cost approach</td>
<td>Short-/mid-term: tuned to meet Current Policies Scenario of WEO, long-term: regional trend proj. for end-use sectors</td>
</tr>
<tr>
<td>GHG emissions</td>
<td>Full basket of Kyoto gases</td>
<td>CO2 only, can be linked to ENV-linkages for non-CO2</td>
<td>Full basket of Kyoto gases</td>
</tr>
<tr>
<td>Production</td>
<td>Perfect markets with CRS-technology (nested CES)</td>
<td>Energy market equilibrium</td>
<td>Perfect markets with CRS-technology (nested CES)</td>
</tr>
<tr>
<td>Capital accumulation</td>
<td>Solow–Swan neoclassical growth model</td>
<td>–</td>
<td>Solow–Swan neoclassical growth model</td>
</tr>
<tr>
<td>Investment dynam.</td>
<td>Old (lower substitution between factors) and new capital vintages, implies longer adjustment of quantities to price changes, increasing weight to services</td>
<td>Capacity additions based on changes in peak demand to previous year, retirement, and governmental policies; increasing weight to services</td>
<td>Vintages for energy supply technologies, adjustment costs for acceleration of capacity expansion</td>
</tr>
<tr>
<td>Share of technologies</td>
<td>Determined by relative prices, depending on substitution elasticities</td>
<td>Determined by regional long-run marginal costs (Logit and Weibull functions)</td>
<td>Determined by relative prices, depending on substitution elasticities</td>
</tr>
<tr>
<td>Price development</td>
<td>Exogenous trends</td>
<td>Exogenous trends</td>
<td>Endogenous</td>
</tr>
<tr>
<td>International trade</td>
<td>Bilateral, Armington-trade</td>
<td>No information</td>
<td>To and from a global pool</td>
</tr>
</tbody>
</table>

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For the documentation of REMIND refer to Luderer et al. (2013).
subsidies is a gap between a reference price (hypothetically the price establishing in a free market) and the actual price paid by an end-user. In general, producer subsidies are more common in developing countries whereas consumer subsidies exist largely in developing countries and in countries of the Former Soviet Union (Ellis, 2010; Koplow et al., 2010). This is also mirrored in the database on subsidies for fossil fuel consumption (International Energy Agency, 2013) and the OECD-inventory (OECD, 2012). Both estimate the amount of subsidies from the consumer-price wedge (price-gap method) basing the reference price on international prices (incl. quality adjustments, freight costs, insurance and distribution costs, as well as Value Added Taxes). The data base includes consumer subsidies for 37 countries from 2007 to 2011 for coal, oil, gas, and electricity. We used these data to derive consumer subsidy rates for each REMIND region, while producer subsidies have to be left out due to lack of data. Additionally, taxes on fossil fuels have been estimated (own estimates, other sources: EU-Council, 2003; GTZ, 2009; FFI, 2011). Based on the calibration of final energy demand in the model base year in 2005, the total amount of subsidies is 350.2 billion USD (2005). Thereby, the region Middle East Asia (MEA) accounts for about 42% followed by Other Asia (OAS) and Latin America (LAM) with 17% and 14%, respectively. Relative to GDP (in purchasing power parity), the ranking differs: At the top is still MEA with 4.8% followed by Russia with 1.8% and OAS with 1.5% relative to their GDP. No subsidies are assumed for the European Union (EUR), Japan, and USA. For further methodological details and base year numbers refer to Appendix A.1, Tables A3 and A4.

Fossil fuel subsidies derived as described above yield values that are of comparable magnitude as used in the other two models: In 2010 global modelled subsidies amount to about 409 billion USD (World Energy Model/ENV-Linkages) and 440 billion USD (REMI). Of this total amount 50% (World Energy Model/ENV-Linkages) and 56% (REMI) are for oil. Note again that we only account for consumer subsidies. Therefore, the total amount of fossil subsidies is underestimated (see as well Koplow et al., 2010). It should also be pointed out that the REMIND model does not explicitly consider subsidies to encourage the deployment of renewable energies. However, some regions have targets for the share of renewables in electricity production (see also Table A6). Furthermore, the combination of an optimal growth model with perfect foresight and global learning curves for renewable technologies yields a positive externality in form of a price decrease for the future which in turn promotes their ramp-up before current market prices are competitive.

### 2.3. Scenario set-up

As mentioned above our scenario set-up spans two policy dimensions. Table 2 gives an overview, including also the comparable scenarios used in the studies by the other two models ENV-Linkages and the World Energy Model. In the climate policy dimension we gradually increase the stringency in the level of climate targets from a reference scenario without climate policy (NoPol-Ref) over a moderate policy baseline (FragPol-Ref) to a 450 ppm stabilization goal (450Pol-Ref). Note that the moderate policy baseline includes current and planned regional climate policies, i.e. emission reduction targets (a moderate interpretation of Copenhagen pledges), technology targets, and carbon intensity projections beyond 2030. For an overview of the detailed targets for each region see Table A6.

The second scenario dimension is that of the phase-out of fossil fuel subsidies. In the reference case (Ref) both taxes and subsidies are held constant at current levels. In that case, by 2020 subsidies make up 0.7% of global GDP in REMIND as well as in ENV-Linkages. This corresponds to about 730 billion USD in REMIND. There are three scenarios with increasing stringency of the phase-out of subsidies. In order to clearly isolate the effects of the subsidy phase-out fossil fuel taxes are held constant in all of those. The first two scenarios cover partial phase outs based on currently published plans. An optimistic interpretation of the G-20 initiative of reducing subsidies mentioned in the beginning is the scenario G20. We assume a gradual reduction by 2020 for China (all subsidies by 50%, India (heating oil by 100%), Latin America (subsidies for Argentina, all oil subsidies for Mexico), OAS (coal subsidies for Korea, oil and gas subsidies for Indonesia), and Russia (all categories reduced by 100%). There are no changes in Africa (AFR), Middle East Asia (MEA), and the Rest of the World (ROW).
In the extended APEC-G20 scenario (G20plus), we assume that APEC as an important Asia-Pacific economic forum also joins the initiative and the G20 as well as the APEC countries completely phase-out their subsidies on the consumption of fossil fuels. Additionally, Iran and Nigeria are reducing their subsidies as indicated in national plans. Thus, some subsidies still remain with MEA (for oil, electricity, and gas), LAM (for oil, electricity, and gas), OAS (mainly for electricity and gas), ROW (gas), and AFR (electricity). In both of these partial phase-out scenarios the level of subsidies achieved in 2020 is held constant after that. An overview of these targets is also given in Table A5. Finally, a complete phase-out of all subsidies (all regions, all types) by 2020 is assumed in the scenario Zero2020, with zero subsidies after that.

3. Discussion of results

A phase-out of subsidies is expected to have two main effects: on domestic demand in the region undertaking the phase-out and on prices of fossil fuels in the world market due to the changes in demand. Though domestic consumers and producers will react with lower demand and adjust to lower market prices, respectively, when subsidies are being removed, a net benefit of such a removal is generated due to reduced government spending. At the global level, we illustrate total price-quantity effects of a subsidy phase-out in Fig. 1. The black squares indicate the reference scenario (Ref), the black triangles the respective subsidy phase-out scenario. Two connected points are at the same point in time, the colour of the connecting line indicates the year. The arrow indicates the shift from a scenario with subsidies to one with a phase-out. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

In the extended APEC-G20 scenario (G20plus), we assume that APEC as an important Asia-Pacific economic forum also joins the initiative and the G20 as well as the APEC countries completely phase-out their subsidies on the consumption of fossil fuels. Additionally, Iran and Nigeria are reducing their subsidies as indicated in national plans. Thus, some subsidies still remain with MEA (for oil, electricity, and gas), LAM (for oil, electricity, and gas), OAS (mainly for electricity and gas), ROW (gas), and AFR (electricity). In both of these partial phase-out scenarios the level of subsidies achieved in 2020 is held constant after that. An overview of these targets is also given in Table A5. Finally, a complete phase-out of all subsidies (all regions, all types) by 2020 is assumed in the scenario Zero2020, with zero subsidies after that.

3.1. Impacts on the mitigation of climate change

The phase-out of subsidies on fossil fuels is often cited by NGOs as one measure to reduce greenhouse gas emissions and possibly an important step towards achieving emission targets set to curb climate change (Bast et al., 2012; Koplow, 2012). Our results
support that notion in the sense that all phase-out scenarios lead to reduced greenhouse gas emissions in comparison to the reference case. We consider here the total emissions of CO₂, N₂O, and CH₄. Over the whole time frame until 2100 the cumulative savings range from 50.6 Gt (0.6%) in the G20 scenario² to 220.8 Gt (2.7%) in scenario Zero2020. However, this is very small compared to reductions achieved in climate policy scenarios. The FragPol-Ref scenario yields cumulative savings of 1285.5 Gt (15.6%). A scenario achieving a GHG concentration of 450 ppm by 2100 (approximately reaching the 2-degree target set by the international community, refer to Meinshausen et al., 2009; UNFCCC, 2009) essentially reduces annual emissions to zero by the end of the century.

Looking at global emissions over time and comparing to the reference case (Fig. 2), largest drops in emissions occur in the middle of the century in all phase-out scenarios without climate policies. The strongest and most immediate reduction is seen in the Zero2020 scenario, consistent with the quick, complete phase-out in all regions, while the G20 scenario has the smallest effect on emissions. However, it is important to note that these emission reductions are not sustainable. By the end of the century, all phase-out scenario emissions are returning to the same level as in the reference case, since the effects of the phase-out are less important than other effects that drive emissions like population, GDP growth, or resource depletion. On the other hand, the two scenarios with climate policies are quite different, reducing emissions also in the long run according to the set policy goals. The FragPol-G20 scenario stabilizes emissions around 2060, while in the 450Pol-G20 case they continue to drop to zero. Clearly the phase-out of fossil fuel subsidies has a much weaker effect on the reduction of fossil fuel use (and therefore emissions) compared to a defined climate policy target, as also discussed in Section 3.3.

These results are supported by good agreement with the previous studies. Relative reductions seen in REMIND of 3.6% in 2020 for the Zero2020 scenario are close to the value of 4.7% found by the World Energy Model (refer to WEO, 2010, 2011). By 2050 the relative reductions in REMIND are only slightly lower (5.3% vs. 5.8%). The ENV-Linkages model studies reductions in 2050 with a focus on regional differences (Burniaux and Chateau, 2011) instead of dedicated climate policies. We find relative reductions in 2050 which are somewhat lower in comparison, but similar in overall orders of magnitude (6.4% reduction of global emissions in the Zero2020 scenario vs. 8% in Burniaux and Chateau, 2011).

Burniaux and Chateau (2011) also discuss the carbon leakage effect connected to the increase of fossil fuel demand, imports and consequently emissions in regions without fossil subsidies due to lower world market prices (rebound effect discussed above). To investigate this, and for a direct comparison with Burniaux and Chateau (2011), we plot regional CO₂ emissions accumulated over the century in comparison to the reference case (Fig. 3). While the REMIND regional configuration is not quite the same as in ENV-Linkages, our regional distribution of emissions decreases and increases is very similar, though the relative effects are somewhat smaller. Note that Burniaux et al. only look at the year 2050, which we do not believe to be sufficient since effects can change over time as discussed above.

Emmission increases due to the carbon leakage effect are seen in the phase-out scenarios for Africa, Europe, USA, and Japan. It is strongest in the Zero2020 scenario for Europe, USA, and Japan. However, it should be emphasized that, despite the leakage effect, on the global level, net emission reductions are seen, with highest reductions in the Zero2020 scenario. Therefore leakage does not provide a convincing counter-argument to phasing-out of subsidies. The leakage effect is overcome by climate policy, though in the fragmented policy case this is only true for those regions with strong climate policies, while an even larger leakage increases emissions in Africa and Japan. The effects of fragmented climate policies are discussed in more detail in Aboumahboub et al. (accepted for publication) and Currás et al. (in press). In the 450Pol scenario, the policy goal dominates strongly and the small differences between phase-out scenarios carry no weight anymore.

³ To increase readability, scenarios without climate policy are not specified with “NoPol”, but only named after the subsidy phase-out scenario, i.e. G20 means NoPol-G20. Policy scenarios are named specifically if they are discussed.

Fig. 2. Greenhouse gas emission pathways for the different phase-out scenarios without climate policy as well as, for comparison, for two policy cases (upper panel). The lower panel zooms in on emission pathways of the phase-out scenarios only, showing them relative to the reference case. GHG included are CO₂, N₂O, and CH₄.

Fig. 3. Changes in cumulative regional CO₂ emissions from 2005 to 2100 for different phase-out scenarios without climate policies and, for comparison two cases with climate policies, relative to the reference case. Oil exporters include ROW, Russia, MIA, and USA. OECD includes the regions ROW, Europe, Japan, and USA. Without climate policy, the carbon leakage effect is clear, though emissions are reduced on the global level.
The two main exporting and subsidy paying regions generally show mixed reaction to the phase-out scenarios, which can be explained with their individual phase-out goals. In the G20 scenario, MEA hardly shows changes in cumulative emissions, while it is affected strongly in the other scenarios. The reason is that MEA does not reduce subsidies in the G20 scenario and its domestic fossil fuel consumption stays at the same level. Russia on the other hand reduces all its subsidies to zero already in the G20 scenario. Moreover, fossil fuel imports are not expanding in Russia. We therefore observe similar emission reductions across all phase-out scenarios. It should be stressed that Russia is the region with the largest emission reductions (almost – 15% while all other regions stay below 4%). This region's ambitious goals to remove fossil fuel subsidies (van Gelder et al., 2010) do clearly set it apart from the limited goals of the other G20 members. MEA, on the contrary, is the region with the highest level of subsidies but modest reduction plans. It only shows a large effect on emissions in the Zero2020 scenario.

From this discussion, taking into account the long-term perspective of REMIND, it becomes clear that, contrary to previous assumptions, e.g. in WEO (2010), long-term mitigation targets only benefit to a very limited degree from emission reductions achieved via fossil subsidies removal. In the short term (until 2020), the strongest phase-out scenario (Zero2020) achieves a reduction of greenhouse gas emissions of 1.6 Gt CO2 or 3.6%. In comparison to the pathways in the FragPol or even 450 ppm climate policy scenarios, this amounts to about 27% and 13% of the necessary reductions, respectively. A combination with climate policies, as for example shown for the FragPol-G20 scenario, is essential, also to overcome the leakage effect.

3.2. Implications for the distribution of welfare

As subsidies for fossil fuels are market distortions, welfare gains in the phase-out scenarios are expected in comparison to the reference scenario. Note that, as the focus is on subsidies, a constant level of equally distorting taxes is used in the scenarios. This prevents welfare gains to be achieved to the largest extent theoretically possible. Being a main driver of the welfare optimization in REMIND, we use the total net present value of consumption over the whole simulation period (2005–2150) as an welfare indicator. The inclusion of current accounts is not necessary, as these are required to balance out over this time. The discount rate is 5%. Again we emphasize that, as the sign of the effect can change from year to year, the evaluation via a cumulative approach is preferred over focusing on one year alone.

We first discuss the case without climate policies. On the global level, total consumption increases in all phase-out scenarios, strongest in the Zero2020 scenario and only marginally in the G20 scenario (Fig. 4). Regionally, “winners” and “losers” can be identified, related to their levels of subsidies, their phase-out goals and their role as an exporter or importer of fossil fuels as discussed above. The largest gains are realized in India, OAS, Africa, and China, i.e. in developing regions with medium levels of subsidies and large dependencies on fossil imports. They profit from price drops of fossils on the world market due to the subsidy phase-out as discussed above. The winning regions found with REMIND are in agreement with the results of Burniaux and Chateau (2011), though the magnitudes cannot be compared as the measures are different.4 The regions without subsidies (Europe, Japan, and the USA) show very little impacts, the USA together with ROW are the only regions with small consumption losses. They are both fossil exporters, though on a much smaller scale than MEA and Russia. The results for these two big exporters depend on the scenario and are exactly opposite. In the G20 scenario, Russia gains significantly, largest among all regions, while MEA loses equally strong. The

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4 Due to the lack of regional markets in REMIND, a calculation of the equivalent variations in income as done in Burniaux and Chateau (2011) is not possible.
Discussion of Results

contrary is true for the G20plus and in particular the Zero2020 scenario. This can be explained again by the different subsidy removal targets as well as by the different trade developments of the two regions. In the G20 scenario, MEA has no phase-out while Russia phases out all subsidies. Regarding the two exporters with their largest levels of subsidies this can almost be seen as a unilateral removal of subsidies by Russia. World market prices drop only a little, as the overall removal of subsidies is not too large and the global demand for fossil energy resources barely drops. Russia then benefits several-fold – domestically due to the money saved from subsidies as well as from domestic efficiency gains, and also through its income increases over time as an exporter. With the lower domestic demand more fuels are available for export at only slightly reduced world market prices. MEA on the other hand has no subsidy reductions and suffers somewhat from the lower global demand and prices.

Global demand drops more significantly in the G20plus scenario and substantially when all subsidies are phased-out in the Zero2020 case, where the prices also drop strongest. This leads to welfare losses for the large exporter Russia as the export revenues fall, thereby off-setting positive efficiency gains. MEA initially benefits through domestic effects caused by the removal of its large subsidies as well as from an increase in its gas export compared to the other scenarios. However, over the course of the century it reduces its exports of oil and gas almost completely, while Russia remains an exporter. These results of the benefit of essentially unilateral removals (in the G20 scenario for Russia) with shifts in the case of multilateral removals (G20plus, Zero2020) are consistent with Burniaux and Chateau (2011) and with theory as discussed above.

Differences between phase-out scenarios are strongly reduced in the cases with climate policy, in particular with a 450 ppm goal. This is due to the larger costs of the mitigation policies, which dominate the behaviour and lead to global consumption losses. In the FragPol scenarios, this is especially true for regions with more ambitious goals like Europe, while China, India, Russia, OAS, MEA, and Africa (having no or small emission reduction goals) still show some dependence on phase-out scenarios. Africa and OAS are the only clear winners in the FragPol case, while India gains under the more extensive phase-out scenarios, but loses in the reference and G20 cases. These regions do not have any or only weak targets in the moderate policy baseline and remain importers of fossil fuels, benefiting from the price drops due to the overall lowered demand in such a climate policy world. MEA does not have policy goals either but as a fossil exporter suffers from the price drops. However its losses are still smallest in the complete phase-out (Zero2020) scenario – the positive effect of the removal of its large subsidies still has an effect. Finally it is possible to decompose the consumption effects into various contributions as shown in detail in Lüken et al. (2011), Luderer et al. (2012b) and Aboumahboub et al. (accepted for publication). Some of these components stemming from the energy system are discussed in more detail in the following sections.

### 3.3. Triggering a sustainable transition of the energy system?

Phasing out subsidies for the consumption of fossil fuels can potentially support a sustainable transition of the domestic energy system via two basic causal chains. Both are connected with higher end-user prices induced by the reduction of subsidies. Firstly, this may lower total (domestic) consumption of final energy (efficiency increase). Secondly, higher end-user prices may also trigger a substitution of fossil fuels by cleaner alternatives (cleaner production). These domestic effects, however, can be offset by the rest of the world as energy markets are globally connected: price differentials between alternative fuels do not only change domestically but also at world markets (as already discussed in Section 3.1). Therefore, it is not a priori clear whether a removal of fossil fuel subsidies supports a sustainable transition. Notably, a large reduction in demand for a particular fuel can also lower international prices to an extent that the demand for energy carriers in regions abroad increases – the second manifestation of the rebound effect. It depends on a region’s responsiveness to price changes. In addition, there is also a potential backlash connected with substituting fuels. The key factor for a net benefit w.r.t. a sustainable transition is to trigger a shift towards cleaner technologies and not, e.g. a substitution of oil by coal causing an expansion of carbon active pollutants (Krewitt, 2002; GEA, 2012). In the following, we discuss the results obtained with REMIND regarding the two causal chains.

Table 3 shows net-savings in global energy demand for different fossil fuel phase-out scenarios combined with varying degrees of climate policies. A complete phase-out of fossil fuel subsidies (Zero2020) leads to a reduction by 20–26 EJ (4–6%) in the year 2020 assuming no climate policies or moderate, fragmented policies (NoPol-Zero2020, FragPol-Zero2020). In contrast, the implementation of G20-plans results only in a reduction by 5–15 EJ moving along the same policy dimensions. The amount saved in Zero2020 (20–26 EJ) is comparable to the results of the WEO model (25 EJ (4%) for a complete phase-out and 19 EJ for a modest phase-out in the New Policies Scenario, WEO, 2011). Note that global energy savings were slightly higher (by 5%) in WEO (2010) and Burniaux and Chateau (2011) as input data for fossil fuel subsidies differ. Table 3 also shows that energy savings are largest in the next decades for no or moderate climate policies. By 2100 savings amount to just 32–46 EJ in total (NoPol and FragPol combined with Zero2020). However, the largest benefit is not generated along the fossil fuel subsidies axis but along the climate policy axis: In the 450 ppm climate stabilization scenario a reduction by 241 EJ (24%) is achieved already without any removal of subsidies. A complete removal just adds 3%. As shown in Fig. A1, most important net-savings are realized in countries removing fossil fuel subsidies, i.e. in MEA, Russia, India, and LAM while USA, EUR, Japan, and ROW expand their demand due to decreasing world market prices for fossil fuels. But this rebound effect is small and it even reverses in the presence of stringent climate policy. This is consistent with the results on GHG emissions discussed earlier.

We now turn to the discussion of substitution processes triggered in the energy system. We first analyze substitutions taking place among fossil fuel resources and second, we study how the share of low carbon technologies changes across scenarios. The first remarkable finding is that the amount of solid coal used in final energy increases substantially in mid-term when subsidies phase out, refer to Fig. 5. This is accompanied by an increase of the
share of coal in primary fossil resources, e.g. from 29% in 2020 to 47% in 2100 in the no policy reference case. This renaissance of coal as a final energy carrier is not only fueled by a boost in its domestic consumption as world prices fall (in India, China, OAS, LAM, and AFR) but also by increases in the amount of coal traded. For example, almost all coal extracted in Russia and the USA is dedicated to export. It is worth mentioning that coal export becomes remunerative for the EU under fragmented climate policies towards the end of the century in G20plus and Zero2020. The revival of solid coal can only be prevented if a global, stringent climate policy regime is in place (compare with 450 ppm scenarios in Fig. 5). In a 450 ppm scenario, higher carbon prices offset the comparative price advantage for coal from phasing out fossil fuel subsidies. Note also that in the 450 ppm scenarios the shares of electricity, heat, and hydrogen in final energy are growing with time. This transition towards modern, grid-based technologies is accelerated by removing fossil-fuel subsidies, albeit the lion’s share clearly originates from climate policies.

The renaissance of solid coal when phasing out fossil fuel subsidies in scenarios without or fragmented climate policies is striking. Is it due to a substitution within coal processing technologies? Is coal replacing oil and gas? Are low carbon technologies crowded out? We find evidence for all, however it needs to be kept in mind that overall phasing out fossil fuel subsidies still leads to net-savings in final energy. It should also be pointed out that the results are somewhat dependent on model assumptions: Assuming a high substitution elasticity between final energy types for heating, the use of solids has a comparative advantage. Furthermore, if it is less favourable to use coal for other purposes than as a solid, this type of consumption will increase. This is the case in the subsidy phase-out scenarios, as subsidies for solid coal use are comparatively low. Therefore the phase-out of all subsidies increases the attractiveness of solid coal use. Note finally that in an intertemporally optimizing framework expectations about future price developments and resource availability also influence today’s decisions.

Despite the renaissance of solid coal, in all scenarios less fossil resources are extracted over the century (Table 4). Yet again, while a phase-out of subsidies unlocks energy savings in final energy, the decisive contribution stems from climate policies which provide stronger incentives to leave fossil resources under ground. In the absence of climate policies, the extraction of fossil resources altogether is reduced by 1−4% compared to the reference scenario. In the case of fragmented climate policies, a reduction by 9−11% is possible (for FragPol-Ref: −7%). In 450 ppm scenarios subsidies have relatively little impact. Phasing out fossil fuel subsidies even causes an additional rise of resource extraction in the short-term for NoPol-Zero2020 and FragPol-Zero2020 (about 3% in 2020) and in the long-term for FragPol-G20 and FragPol-G20plus (up to 4% in 2100). Moreover, short-term expansions are connected with net-increases in the use of coal which is most pronounced in Zero2020. Only in later decades net-savings in coal are realized. As shown in Fig. 6, the increase in coal used as solids is only later compensated by decreasing amounts of coal used for electricity and liquids. This finding mirrors the set-up of the subsidy scenarios (note that the end-use of solids is less subsidized compared to liquids and electricity corresponding to a comparative price-advantage).

However, the phase-out of fossil fuel subsidies affects the composition of primary energy carriers. Remarkably, the share of renewables in primary energy consumption is affected by a subsidy phase-out in an unfavourable way w.r.t. a low carbon transition (Table 5). While the share of renewables is growing with the stringency of climate policies, this is not always the case when subsidies are being removed. Towards the end of the century, the...
4. Conclusions and policy implications

This paper is the first to study effects of fossil fuel subsidy phase-out scenarios with an intertemporal optimization model covering the whole 21st century. This provides the opportunity to compare to results found previously with other models and to assess their robustness (WEO, 2010, 2011; Burniaux and Chateau, 2011). In addition, it enables the exploration of different effects due to the different modelling approaches. We confirm the magnitude of greenhouse gas emission reductions and global net energy savings found in previous studies as positive global effects of phasing out fossil fuel subsidies. The carbon leakage effect plays little role, since emission increases in some regions are smaller than the reductions in others. We also find a global gain in consumption, albeit differences in the regions. Developing regions that import fossil fuels (India, China, OAS, Africa) are “winners”, while results for exporting regions such as Russia and MEA are mixed. The balance of increasing exports due to falling world market prices for fossil resources, increasing domestic efficiency, and overall lower global demand matters. It plays out differently in across scenarios. For Russia, an almost unilateral phase-out (G20 scenario) seems more beneficial than multi-lateral action.

We find it to be of great importance not only to focus on the next few decades but also to take into account the long-term effects when designing policies to phase-out fossil fuels. We show that phase-out achievements (savings in net energy and the greenhouse gas emissions reductions) are short-lived and pathways shift back towards the reference case by the end of the century. Thus, the long-term gains are small. In 2100 the extraction of fossil resources is reduced by not more than 5% if subsidies are completely removed. The total amount of greenhouse gas emissions saved reaches only 15% of the reductions achieved in the current climate policy scenario (FragPol-Ref), which is still far from what would be needed to reach a 2-degree target. In fact, the greenhouse gas emissions in our phase-out scenarios in the year 2020 are around 59–60 Gt CO₂eq per year, which is above the range “preserving the option of meeting a 2 °C target”, as recently found by Rogelj et al. (2013). It is therefore misleading to judge effects based on the short-term results only. Policy initiatives to phase-out fossil fuel subsidies are by far not sufficient to compensate for stringent climate policies on a global scale, or to even deliver a considerable step along the way. However, it should be noted that such initiatives can instigate political and societal dynamics leading to more stringent long-term goals, which we cannot capture in our model.
In line with that, our analysis further reveals that substitution processes resulting from a fossil fuel phase-out need to be carefully taken into account. Using an intertemporal optimization model we find that a complete phase-out of fossil fuel subsidies leads to a substitution within coal technologies towards solids. This renaissance of solid coal is caused by the comparatively low subsidies paid for it as fuel. In a subsidy phase-out scenario, this fuel therefore gains in relative competitiveness, even though oil and gas prices also drop. A competitive price advantage is also given compared to renewable and nuclear resources. Furthermore, more coal is available for direct use as a solid fuel, since the demand e.g. for coal-to-liquid conversion declines. Countries therefore increase coal extraction to realize trade benefits. As this effect is also prevailing in climate policy scenarios (i.e. a fossil fuel phase-out leads to a decrease in the price of carbon), low carbon resources face a disadvantage which would have to be compensated to make them competitive. A detailed study of ways to offset such unfavourable developments while reducing fossil fuel subsidies is left to future work.

To some degree these results are influenced by the consideration of consumer subsidies only. This is dictated by a lack of data on producer subsidies as mentioned in Section 2.3. On one hand producer subsidies are estimated to amount to about 100 billion USD (one-fifth of consumer subsidies in 2011). Yet, a recent report on progress with the implementation of G20 initiatives states that in particular producer subsidies for coal in Australia, USA, and Canada are on the rise (G20-Report, 2012). Taking them into account explicitly and modelling their phase-out would influence our result on the coal renaissance. However, the direction of this influence could be a decrease or an increase depending on whether subsidies are used to directly support the extraction of resources or not.

Like any model, certain characteristics of REMIND also lead to limitations of this study. In particular we should note again the limited regional resolution (REMIND is limited to 11 world regions) and the limited, i.e. only stylized, representation of end-use sectors. Furthermore, REMIND only implicitly accounts for energy infrastructure (e.g. power grid, transportation, pipelines). Also, REMIND does not distinguish between rural/urban population and there is no sub-regional differentiation of access to energy services (e.g. electricity). Hence, we can say little about the implications for households with low income. Furthermore, the assumed high substitution elasticity between final energy types for heating benefits the use of solids and the coal renaissance. Finally, strategic behaviour of resource exporters is not considered.

Politically, a complete phase-out of fossil fuel subsidies currently does not seem realistic. According to the recent G20-Report (2012) “G20 failed to advance the progress in this regard”. On the other hand, the G20 also has goals to improve energy efficiency and to increase the share of clean technologies. These goals seem to find a higher level of agreement among the G20 members. As our results show, these goals are complementary to a removal of fossil fuel subsidies, which by itself does not lead to high emission savings and a transformation towards a low-carbon energy system. Nevertheless, ultimately the achievement of ambitious climate targets requires some form of a global carbon price regime, for which the prospect is currently unclear.

Acknowledgements

We are thankful to all members of the REMIND team for ongoing fruitful discussions. We thank Eva Schmidt for helpful suggestions to improve the manuscript and Jenny Rieck for her support in the documentation of data. All remaining errors remain the sole responsibility of the authors. The research leading to these results has received funding from the European Union’s Seventh Framework Program [FP7/2007-2013] under Grant agreement nos. 265139 (AMPERE) and 266992 (Global-IQ).

Appendix A. Model assumptions

A.1. Comparison of regional and macro-economic assumptions

Native model regions are defined as follows (note that countries are abbreviated using 3-digit country codes):

- REMIND resolves 5 countries (CHN, IND, JPN, RUS, USA) and 6 macro-regions (AFR – Subsaharan Africa without ZAF, EUR – European Union, LAM – Latin America, MEA – Middle East Asian countries incl. North Africa and stan-countries of FSU, OAS – Other Asia, ROW – Rest of World). Refer to Luderer et al. (2013) for a detailed documentation of the model.

- The World Energy Model resolves 12 countries (BRA, CAN, CHE, CHN, IND, IDN, JPN, KOR, MEX, RUS, ZAF, USA) and 13 macro-regions (OECD Europe with 3 regional models, OECD Asia Oceania with 2 country models and the region AUS–NZL, Easter Europe/Eurasia with 1 country and 3 regions, Non-OECD Asia with 3 country models and 2 regions, LAM with BRA and the rest of the region, Middle East as 1 region, Africa with 1 country and 2 regional models comprising the whole continent). Refer to International Energy Agency (2012) for further details.

- ENV-Linkages resolves 7 countries (BRA, CAN, CHN, IND, JPN, RUS, USA) and 5 macro-regions (AUS–NZL; European Union and EFTA; Oil producing countries with IDN, VEN, Rest of Middle East,

<table>
<thead>
<tr>
<th>Table A1</th>
<th>Comparison of annual compound GDP growth rates for selected regions. Sources: WEO (2012) and baseline of REMIND.</th>
</tr>
</thead>
<tbody>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>AFR</td>
<td>2.5</td>
</tr>
<tr>
<td>CHN</td>
<td>9.9</td>
</tr>
<tr>
<td>EUR</td>
<td>2.1</td>
</tr>
<tr>
<td>IND</td>
<td>5.6</td>
</tr>
<tr>
<td>JPN</td>
<td>1.1</td>
</tr>
<tr>
<td>LAM</td>
<td>2.9</td>
</tr>
<tr>
<td>MIA</td>
<td>3.8</td>
</tr>
<tr>
<td>RUS</td>
<td>3.9</td>
</tr>
<tr>
<td>USA</td>
<td>3.4</td>
</tr>
<tr>
<td>World</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Asterisks indicate that native model regions do not exactly match among the models.
IRN, Rest of North Africa and NIG; Rest of Annex 1 countries with CRV and Rest of FSU; Rest of World). Refer to Burniaux and Chateau (2010) for further details.

Assumptions on economic growth are compared in Tables A1 and A2.

A.2. Base year calibration of fossil fuel subsidies

We used the IEA database on subsidies for fossil fuel consumption (International Energy Agency, 2013) which contains data for 37 countries (2007–2011). Data are broken down to 4 categories: coal (incl. hard coal, lignite, peat), oil (incl. LPG, gasoline, diesel, kerosene), gas (natural gas), and electricity (excluding subsidies for nuclear and renewable energy). Recently, 2011 data became available. Oil subsidies increased strongly in India, China, Algeria, Venezuela, and countries in Asian Oceania. Other categories’ changes are small.

To calibrate subsidies for the base year 2005, we took the average of 2008–2010. Using energy demand data for 2008–2010 (Source: ENERDATA), base year subsidies for coal, oil, gas, and electricity have been allocated to final energy types as represented in REMIND. These are solids, heating oil, gas, and electricity used in residential, commercial, and industrial sectors.

### Table A2
Comparison of annual compound growth rates for selected model regions. Sources: Duval and de la Maisonneuve (2010) and baseline of REMIND.

<table>
<thead>
<tr>
<th>Model region</th>
<th>OECD</th>
<th>REMIND</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHN</td>
<td>8.3</td>
<td>5.0</td>
</tr>
<tr>
<td>EU**</td>
<td>1.6</td>
<td>2.1</td>
</tr>
<tr>
<td>IND</td>
<td>7.4</td>
<td>6.7</td>
</tr>
<tr>
<td>JPN</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>MEA**</td>
<td>4.6</td>
<td>4.7</td>
</tr>
<tr>
<td>RUS</td>
<td>3.1</td>
<td>2.6</td>
</tr>
<tr>
<td>USA</td>
<td>1.9</td>
<td>2.4</td>
</tr>
<tr>
<td>World</td>
<td>3.4</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Asterisks indicate that native model regions do not exactly match among the models.

### Table A3
Allocation of subsidies for fossil fuel consumption to REMIND regions (37 countries) and G20 members in REMIND regions (boldface), APEC members. Subsidy information based on International Energy Agency (2013).

<table>
<thead>
<tr>
<th>Region</th>
<th>Data coverage and member economies of G20 and APEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFR</td>
<td>Data: AGO, NGA</td>
</tr>
<tr>
<td>CHN</td>
<td>Data available, member of G20 and APEC</td>
</tr>
<tr>
<td>EUR</td>
<td>No data, G20 members: DEU, FRA, ITA, ESP, GBR</td>
</tr>
<tr>
<td>IND</td>
<td>Data available, member of G20</td>
</tr>
<tr>
<td>JPN</td>
<td>no data, member of G20 and APEC</td>
</tr>
<tr>
<td>LAM</td>
<td>Data: ARG, COL, SLV, ECU, MEX, PER, VEN</td>
</tr>
<tr>
<td>MEA</td>
<td>Other G20 members: BRA, APEC members: MEX, CHL, PER</td>
</tr>
<tr>
<td>OAS</td>
<td>Data: BGD, IDN, MYS, PAK, PHIL, KOR, LKA, TWN, THA, VNM</td>
</tr>
<tr>
<td>ROW</td>
<td>Data: ZAF, UKR; Other G20 members: AUS, CAN, TUR; APEC: AUS, CAN, NZL</td>
</tr>
<tr>
<td>RUS</td>
<td>Data available, member of G20 and APEC</td>
</tr>
<tr>
<td>USA</td>
<td>No data available, member of G20 and APEC</td>
</tr>
</tbody>
</table>

### Table A4
Subsidies for fossil fuel consumptions per category in REMIND regional aggregation in absolute terms [billion USD2005] and relative as % of GDP (purchasing power parity) in the base year 2005. Data are based on International Energy Agency (2013).

<table>
<thead>
<tr>
<th>Absolute subsidies</th>
<th>As percentage of GDP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
</tr>
<tr>
<td>AFR</td>
<td>5.7</td>
</tr>
<tr>
<td>CHN</td>
<td>24.2</td>
</tr>
<tr>
<td>EUR</td>
<td>25.4</td>
</tr>
<tr>
<td>IND</td>
<td>48.3</td>
</tr>
<tr>
<td>JPN</td>
<td>147.0</td>
</tr>
<tr>
<td>MEA</td>
<td>58.1</td>
</tr>
<tr>
<td>OAS</td>
<td>11.6</td>
</tr>
<tr>
<td>RUS</td>
<td>29.8</td>
</tr>
<tr>
<td>USA</td>
<td>350.2</td>
</tr>
</tbody>
</table>

Appendix
Table A5
Subsidy reduction targets for fossil fuel consumption per category in REMIND regional aggregation in USD2005/GJ for the year 2020. Targets are given for the three scenarios Ref→G20→G20plus, a change is indicated in bold. Only one value is given if it does not change in any of the scenarios. All subsidies are removed by 2020 in the Zero2020 scenario. For India there is a reduction of subsidies for heating oil to zero in the G20 scenario, the other oil subsidies remain constant. In all scenarios, the subsidies decrease linearly over time to the target levels in 2020.

<table>
<thead>
<tr>
<th>Region</th>
<th>Coal</th>
<th>Oil</th>
<th>Gas</th>
<th>Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ref→G20→G20plus</td>
<td>Ref→G20→G20plus</td>
<td>Ref→G20→G20plus</td>
<td>Ref→G20→G20plus</td>
</tr>
<tr>
<td>AFR</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CHN</td>
<td>0.11→-0.06→-0</td>
<td>1.36→0.68→0</td>
<td>1.14→0.57→0</td>
<td>2.95→2.95→0.67</td>
</tr>
<tr>
<td>EUR</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>IND</td>
<td>–</td>
<td>–</td>
<td>5.52→5.52→0</td>
<td>3.81→3.81→0</td>
</tr>
<tr>
<td>JPN</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>LAM</td>
<td>0.62</td>
<td>3.55→-2.29→-1.99</td>
<td>1.99→0.71→0.7</td>
<td>2.02</td>
</tr>
<tr>
<td>MEA</td>
<td>–</td>
<td>12.36→12.36→4.51</td>
<td>6.89→6.89→3.5</td>
<td>13.16→13.16→9.4</td>
</tr>
<tr>
<td>OAS</td>
<td>0.27→-0.2→-0</td>
<td>2.62→-1.15→-0.27</td>
<td>3.46→-3.46→2.57</td>
<td>3.91→-2.86→-2.01</td>
</tr>
<tr>
<td>ROW</td>
<td>–</td>
<td>0.01→0.01→-0</td>
<td>1.29</td>
<td>0.96→0.96→-0.31</td>
</tr>
<tr>
<td>RUS</td>
<td>–</td>
<td>–</td>
<td>8.02→0.96→0</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Table A6
Emissions and technology targets for the individual regions in the moderate policy baseline. The target year is 2020 unless noted otherwise, the base year is 2005. The renewable energy share includes wind and solar targets. For RUS the increase in emissions compared to 2005 still means a 15% reduction compared to 1990. For the composite regions ROW, LAM and OAS, where some countries have emission targets and others do not, the target for 2020 is calculated with respect to the emission increase between 2005 and 2020 in the respective BAU run, i.e. it is slightly different for each subsidy removal scenario, hence we give here the range. Compared to the BAU emission increase, the increases in the moderate policy baseline are reduced by 7.7% for OAS and 16.6% for LAM.

<table>
<thead>
<tr>
<th>Target</th>
<th>Across-the-board GHG emission reduction target incl. LULUCF</th>
<th>Modern renewable energy share in electricity production</th>
<th>GHG intensity target</th>
<th>Nuclear energy target</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFR</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CHN</td>
<td>–</td>
<td>25%</td>
<td>–</td>
<td>41 GW</td>
</tr>
<tr>
<td>EUR</td>
<td>– 15%</td>
<td>15%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>IND</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>LAM</td>
<td>–</td>
<td>+23.8 to +24.9%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>MEA</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>OAS</td>
<td>+271 to +32.1%</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>ROW</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>RUS</td>
<td>+27%</td>
<td>–</td>
<td>–</td>
<td>34 GW by 2030</td>
</tr>
<tr>
<td>USA</td>
<td>– 5%</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Fig. A1. Regional differences in final energy in comparison to the reference case (in EJ). Subsidies are increasingly removed from left to right. From bottom to top the stringency of climate policies increases. At the global level net-savings in final energy demand are realized along both dimensions. Regions removing fossil fuel subsidies and/or implementing climate policies reduce their demand strongest. Note the different scales.
in the stationary sector as well as petrol and diesel needed in the transport sector. Additionally, taxes on fossil fuels have been estimated (own estimates, other sources: EU-Council, 2003; GTZ, 2009; FFI, 2011). How subsidies are allocated to REMIND regions is shown in Table A3. Table A4 shows absolute as well as relative amounts of subsidies as percentage of GDP in purchasing power parity (total and categories).

A.3. Targets for the moderate policy baseline (FragPol)

See Table A6.

A.4. Regional results for final energy

See Fig A1.

Appendix B. Supplementary materials

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.enpol.2013.12.015.

References


Chapter 6

Complementing Carbon Prices with Technology Policies to Keep Climate Targets within Reach*

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Complementing carbon prices with technology policies to keep climate targets within reach

Christoph Bertram1,2*, Gunnar Luderer1, Robert C. Pietzcker1, Eva Schmid1, Elmar Kriegler1 and Ottmar Edenhofer1,2,3

Introduction

Economic theory suggests that comprehensive carbon pricing is most efficient to reach ambitious climate targets1, and previous studies indicated that the carbon price required for limiting global mean warming to 2°C is between US$16 and US$73 per tonne of CO2 in 2015 (ref. 2). Yet, a global implementation of such high carbon prices is unlikely to be politically feasible in the short term. Instead, most climate policies enacted so far are technology policies or fragmented and moderate carbon pricing schemes. This paper shows that ambitious climate targets can be kept within reach until 2030 despite a sub-optimal policy mix. With a state-of-the-art energy–economy model we quantify the interactions and unique effects of three major policy components: (1) a carbon price starting at US$7 per tonne of CO2 in 2015 to incentivize economy-wide mitigation, flanked by (2) support for low-carbon energy technologies to pave the way for future decarbonization, and (3) a moratorium on new coal-fired power plants to limit stranded assets. We find that such a mix limits the efficiency losses compared with the optimal policy, and at the same time lowers distributional impacts. Therefore, we argue that this instrument mix might be a politically more feasible alternative to the optimal policy based on a comprehensive carbon price alone.

To limit the mitigation costs and risks of achieving the 2°C target, it is essential to start comprehensive climate policy as early as possible3–7. Recent studies have shown that pledged reductions are not consistent with cost-efficient emissions pathways reaching the 2°C target8–9. Furthermore, a continuation of climate policy at the current ambition level will not lead to a stabilization of climate change10,11, and the delay of more stringent mitigation actions will significantly exacerbate the challenge of reaching long-term climate policy objectives4–6. Current policies fail to induce the transformation of the energy system to the extent required by long-term climate targets and lead to further lock-in into carbon-intensive infrastructure. Not only do too much emissions occur in the near term, but also mitigation later on is rendered more difficult10–12. It is an important question whether technology policies can reduce such lock-in and mitigate the impacts of delay. Although a few studies based on global energy–economy models have considered single packages of technology policies in several countries around the world, their explored this question.

The environmental economics literature has also not focused on the scope of technology policies for overcoming deficiencies in carbon pricing. In this strand of scholarly work, technology policies have mainly been analysed as means to cure market failures beyond the pure pollution externality, for example, due to learning spillovers, information asymmetries and so on13–15. In contrast, here we analyse their complementary role under sub-optimal carbon pricing. There is wide agreement that market-based instruments pricing the externality of emissions have an advantage in terms of efficiency1. At the same time it is debated whether or not setting a price (carbon tax) or a quantity of tradable permits (cap-and-trade) is preferable16–20. Some authors find that the interaction with other instruments favours the price instrument20, a finding that our study extends to the case of sub-optimal carbon pricing combined with technology policies.

This study is the first to assess which mix of emission pricing and technology policies is effective in avoiding further lock-in and initiating the transformation required for limiting warming to 2°C. We thus fill an important gap in the literature by informing the ongoing climate policy debate, which so far revolves around modest approaches to carbon pricing and various forms of technology policies in several countries around the world.

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tantalamountoalackofcomprehensiveemissionspricinginlinewiththe
2°Climit.

Ouralanalysissuggestsacombinationmixthat—basedonthepositive
effects of technology policies under sub-optimal carbon pricing—keeps ambitious climate targets within reach and is possibly
easier to implement politically. It does so by addressing two
crucial questions: (1) how weaker-than-optimal carbon pricing
schemes and additional technology policies interact, and (2) which
combination can best reduce the adverse effects of sub-optimal
carbon pricing.

Tothisend,weemploytheenergy–economy–climate model
REMIND (refs 21,22) for analysing a variety of scenarios with
combined carbon pricing and technology policies in the initial
period of 2015 until 2030, followed by pricing-only policies for
the remainder of the century designed to be consistent with the
2°C climate target. Table 1 provides an overview of the considered
policies along the two dimensions pricing and technology, including
the definitions of the scenario components Opt, Cap, Tax, Zero,
noT, CM, LCS and C&L. To enable a meaningful comparison,
the two pricing policies are chosen such that they coincide in
the case without additional technology policy and with reference
energy demand assumption. The corresponding greenhouse gas
(GHG) emissions level of 60.8 GtCO₂ in 2030 represents a lenient
extrapolation of the Copenhagen pledges4,9. and falls short of optimal
mitigation action with respect to a 2°C target in each of the nine
models participating in the AMPERE study5.

Inadditiontothereference caseswithoutanymore technology
policies, we consider three technology policy packages that imply
the continuation and global roll-out of technology support and
regulation as observed in a number of countries (Supplementary
Fig. 7). The considered policies target developments that have
been identified as robust features of transformation pathways in
previous studies24–26, such as a shift towards low-carbon energy
supply, a phase-out of final energy subsidies (until 2030 instead of
2050), plus international convergence of transport fuel taxes.

We find that the combination of weak carbon pricing with
technology policies falls short of closing the emissions gap in 2030
(ref. 8), with emissions between 56 and 61 GtCO₂ compared with
∼45 GtCO₂ resulting from the optimal carbon price of close to
US$60 per tonne of CO₂ (Fig. 1). Additional technology policies
can result in up to ∼4 GtCO₂ lower emissions at a given price
level (tax regime), or up to ∼70% lower prices to reach a given

**Table 1 | Description of medium-term policy options considered in the scenarios.**

<table>
<thead>
<tr>
<th>Name</th>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pricing dimension: Zero Carbon price</td>
<td>Baseline scenarios with zero carbon price.</td>
<td></td>
</tr>
<tr>
<td>Cap</td>
<td>Sub-optimal carbon pricing implemented as cap-and-trade system</td>
<td>Emission target for 2030: 60.8 GtCO₂ globally, in line with extrapolation of lenient interpretation of Copenhagen pledges4,9.</td>
</tr>
<tr>
<td>Tax</td>
<td>Sub-optimal carbon pricing implemented as carbon tax</td>
<td>Globally uniform carbon tax of US$7.3 per tonne of CO₂ in 2015, increasing at 5% p.a.</td>
</tr>
<tr>
<td>Opt</td>
<td>Immediate optimal carbon pricing with respect to 2°C target</td>
<td>CO₂ budget of 1.500 GtCO₂ for the period 2000–2010 with full flexibility on when and where emissions occur.</td>
</tr>
</tbody>
</table>

**Technology dimension: noT(ech)** No additional technology policy Only the pricing determines technology choice.

- **CM** Coal moratorium Ban on construction of new freely emitting coal-based transformation capacities for electricity, liquids, gas and H₂.
- **LCS** Low-carbon support Minimum targets for global installation of different renewable electricity generation capacities (wind power, photovoltaics, concentrated solar power), CCS deployment (gas electricity and bio-liquids) and electric vehicles. Excess costs for solar and wind generation are refinanced through electricity price mark-ups to avoid rebound effects.
- **C&L** Combined coal moratorium, low-carbon support, tax and subsidy reform Combination of coal moratorium and low-carbon support plus an accelerated phase-out of final energy subsidies (until 2030 instead of 2050), plus international convergence of transport fuel taxes.

All monetary values are given in constant 2013 prices. The Methods section and the Supplementary Information contain further details on the scenario design.

Figure 2 | Global electricity generation by technology. The left panel illustrates absolute numbers in 2030; the right panel shows differences between the benchmark Opt–noT and the different policy scenarios.
emissions level (cap regime). This illustrates how ancillary policies break the symmetry between price and quantity instruments\(^6\). This asymmetry has important implications for the effectiveness of complementary technology policies, and is discussed further below.

In line with previous multi-model studies\(^24,25\), we find that under first-best carbon pricing (Opt–noT), the decarbonization of power supply is already well advanced by 2030 (Fig. 2). Coal is almost completely phased out and low-carbon generation technologies, in particular wind and gas combined with carbon capture and storage (CCS), expand considerably. The right panel shows that the technology policies bring the electricity generation system closer to the optimal configuration, both in terms of total electricity output and technology mix. Nevertheless, in each of the weaker-than-optimal carbon pricing scenarios, freely emitting coal and gas-based power generation is higher and total low-carbon electricity generation is lower than in the benchmark. The additional constraints in the CM, LCS and C&L scenarios in the electricity system lead to higher electricity prices, so total demand and generation decrease. The coal moratorium leads to lower coal prices and thus higher use of coal outside the electricity system, for example, for steel production. This is a case of emissions rebound or inter-sectoral leakage\(^27\) (Supplementary Fig. 3) that reduces the effectiveness of the CM policy. We observe that LCS and CM policies have complementary effects on power sector decarbonization because they act in different directions. Lower coal use does not induce higher use of low-carbon energy as a side effect, and vice versa. Therefore, the combined policy package C&L comes closest to the deployment in the Opt–noT scenario.

The emissions gap\(^8\) or other emission-based indicators of the mitigation challenge\(^6\) do not capture the adverse economic effects of sub-optimal climate policies over the next decades. As more policy-relevant alternatives, we therefore use four indicators of economic and distributional impacts and institutional requirements measured between economic efficiency in terms of long-term costs versus distributional challenges. For example, for steel production. This is a case of emissions rebound or inter-sectoral leakage\(^27\) (Supplementary Fig. 3) that reduces the effectiveness of the CM policy. We observe that LCS and CM policies have complementary effects on power sector decarbonization because they act in different directions. Lower coal use does not induce higher use of low-carbon energy as a side effect, and vice versa. Therefore, the combined policy package C&L comes closest to the deployment in the Opt–noT scenario.

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The comparison of scenarios with and without combined technology policies illustrates an often overlooked trade-off between economic efficiency in terms of long-term costs versus distributional impacts and institutional requirements measured in terms of the carbon value. The efficiency losses as measured

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**Figure 3** | Economic indicators for the long-term challenges of achieving the 2°C target after 2030. **a**. Cumulated discounted consumption loss relative to a baseline without any climate policy from 2010 to 2100. **b**. Cumulated discounted carbon value from 2010 to 2100 (for definition and calculation of these indicators, see ref. 5 and Supplementary Section F).
In the long term, a global economy-wide carbon price at a high level remains a key necessity for reaching the deep decarbonization required for 2 °C stabilization. In the near term, as shown by our work, complementing a moderate carbon price with technology policies can offer a pragmatic entry point to ambitious climate policy.

Methods

We use the integrated energy–economy–climate model REMIND (refs 21,22) to assess the long-term implications of different short-term climate-related policies. REMIND is an inter-temporal, general equilibrium model of the global economy with a technology-rich representation of the energy supply system. It differentiates 11 world regions and runs on 5-year time steps. The model usually operates with perfect foresight over the full modelling time frame 2010–2100. Thus, learning externalities are internalized. Here, we compare two scenarios with sub-optimal policies until 2030, followed by first-best policies that limit global warming to 2 °C. Before 2030, the model does not anticipate the later tightening of emission policies. This leads to an overinvestment into carbon-intensive capital and underinvestment into the scale-up of low-carbon technologies.

REMIND captures crucial aspects of system inertia and path dependencies, as vintage capital stocks of more than 50 energy-conversion technologies as well as technological learning of wind, solar and electro-mobility technologies are represented explicitly. All technologies are subject to cost mark-ups in the case of fast-scaling. Furthermore, the model considers existing final energy taxes and subsidies and the scarcities and constraints driving resource prices.

It has to be stressed that all long-term modelling of the future evolution of the global economy has considerable limitations. The scenarios described in this paper should therefore not be interpreted as predictions, but rather as means for analysing interactions between different policy instruments and energy system developments. Despite the explicit representation of second-best near-term policies, the scenarios still assume idealized conditions in many aspects, for example, optimal saving and investment decisions and full regional cooperation.

Until 2030, two different carbon pricing policies and four different technology policies are combined (Table 1). We define the policies on the global level. Thus, the scenarios establish a benchmark against which national climate policy proposals can be compared. In Cap scenarios, an upper bound on global GHG emissions of 60.8 GtCO₂ in 2030 is prescribed; hence, CO₂ prices until 2030 vary depending on the technology policy scenario. In Tax scenarios, in contrast, the tax rate is fixed across scenarios but GHG emissions in 2030 differ (Fig. 1). We chose the tax rate such that without additional technology policies, the Cap and the Tax scenarios are identical. The path of the tax rate starts at US$7.3 in 2013. In both variants, CO₂ prices until 2030 increase by 5% p.a., jump to the optimal level in 2035 and then increase by the endogenous time variable interest rate in the model of 5–7%.

In the first technology policy option, coal moratorium (CM), no new freely emitting coal-based conversion plants for the production of electricity, liquids and gaseous fuels can be built. To represent the projects under construction, a global total of 150 GW coal-fired electricity plants with technical lifetimes of 35–40 years can be built until 2020. The only freely emitting channel for coal that can be expanded is thus the use of solid coal in industry and for heating purposes.

The second technology option, low-carbon support (LCS), foresees a dedicated push for certain low-carbon options, implemented as a lower bound on their global deployment. For some technologies, such as wind (globally 1.6 TW in 2030), solar photovoltaics (900 GW) and concentrated solar power (18.5 GW) as well as electric light-duty vehicles (27 million vehicles), the implied market developments represent a continuation of market growth observed in the past years (Supplementary Fig. 7). This market growth was the result of policy support such as, for example, feed-in-tariffs. In the model, the extra costs for wind and solar are financed by a premium fee applied to electricity usage. The two additional technologies supported in the LCS scenarios, natural-gas-based electricity generation with CCS and biofuels conversion with CCS are financed out of the general budget. Here, technology policy in the real world has to be ramped up compared with observed policies to foster research, development, demonstration and deployment. The lower bounds in 2030 are 1.4 million barrel oil-equivalent per day for biomass refineries and 50 GW for gas power plants combined with CCS.
The third technology policy variant, coal moratorium and low-carbon support (C&M) is a combination of the other two, with an additional change of final energy taxes and subsidies. Whereas in all other scenarios, final energy taxes stay constant and consumer subsidies are phased out linearly until 2050, C&M scenarios foresee a faster phase-out of subsidies until 2030 and a convergence of transport fuel taxes to a level of −US$0.41\text{ l}^{-1}\text{ CO}_2$. From 2035 on, comprehensive optimal carbon pricing limits the cumulative 2000–2100 CO₂ budget to 1,500 GtCO₂. This implies a 50–60% probability of keeping the increase in global mean temperature in 2100 below 2 °C compared with pre-industrial levels\textsuperscript{30}. Other forcing agents are priced equivalently, on the basis of 100-year global warming potential values\textsuperscript{4}. Further details on the methods can be found in the Supplementary Information.

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References


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Author contributions

C.B. and G.L. designed the research with input by R.C.P., E.K. and O.E.; C.B. performed the modelling and data analysis; C.B. wrote the paper with contributions and edits by all authors.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to C.B.

Competing financial interests

The authors declare no competing financial interests.
Complementing carbon prices with technology policies to keep climate targets within reach

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A. Model description

We use version 1.5 of the energy-economy-climate model REMIND for the calculation of the different policy scenarios analysed in this study. We present here a short model description summarized in table 1, while referring the interested reader to the detailed documentation of REMIND 1.5\textsuperscript{1} and the supplementary materials of Luderer et al.\textsuperscript{2} and Klein et al.\textsuperscript{3} on which the following is based.

Table 1: Key characteristics of the REMIND model.

<table>
<thead>
<tr>
<th>Model feature</th>
<th>Implementation in REMIND Version 1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope</td>
<td>Global coverage, differentiated into 11 regions, 2005-2100.</td>
</tr>
<tr>
<td>Macro-economic core and solution</td>
<td>Intertemporal welfare optimization: Ramsey-type growth model, Negishi approach for regional aggregation</td>
</tr>
<tr>
<td>Substitution possibilities within the macroeconomy</td>
<td>A generic consumption good is generated via a production function with constant elasticity of substitution of 0.5 (CES), with input factors capital, labour, and energy (represented as a nested CES function comprising different final energy types with elasticities between 0.3 and 3).</td>
</tr>
<tr>
<td>Link between energy system and macroeconomy</td>
<td>Economic activity determines demand via the production function; energy system costs (investments, fuel costs, operation and maintenance) are included in macro-economic budget constraint. Energy system and macroeconomy are optimized jointly.</td>
</tr>
<tr>
<td>Technology choice in the energy system</td>
<td>Linear substitution between competing technologies for secondary energy production. Supply curves for exhaustibles (cumulative extraction cost curves) as well as renewables (differentiated by capacity factors) introduce convexities. Mark-ups on investment costs (adjustment costs) penalize rapid expansion of deployment. Early retirement is limited to 4% per year.</td>
</tr>
<tr>
<td>Technological change &amp; learning</td>
<td>Learning by doing (LbD) for wind and solar power and electric vehicles. A global learning curve with floor costs is assumed. LbD spillovers are internalized. Labour productivity and energy efficiency improvements are prescribed exogenously.</td>
</tr>
<tr>
<td>International trade</td>
<td>Global markets for coal, oil, gas, biomass, a generic consumption good and capital. Interregional trade of captured CO₂ or secondary energy carriers is not considered.</td>
</tr>
<tr>
<td>Discounting</td>
<td>The constant rate of pure time preference in the iso-elastic welfare function is 3%. In line with the Keynes-Ramsey-Rule, the intertemporal elasticity of substitution of 1 and an average rate of increase of global per capita incomes of around 3% result in an endogenous discount rate of between 5 and 7%.</td>
</tr>
<tr>
<td>Policy implementation</td>
<td>See section D for technology policies and section E for the climate policies.</td>
</tr>
</tbody>
</table>
REMIND is a global model of the energy-economy-climate system spanning the period 2005-2100, with 5-year time steps between 2005 and 2055, one 7.5-year time step in 2060 and 10-year time steps thereafter. The mentioned years in the paper always refer to the central year of each period (e.g. 2030 stands for the period 2028-2032). The macro-economic core of REMIND is a Ramsey-type intertemporal general equilibrium model in which global welfare is maximised, as found in similar form in other integrated assessment models such as RICE or MERGE. The model computes a Pareto-optimal solution, which corresponds to the market equilibrium in the absence of non-internalised externalities. The world is divided into 11 regions: there are five individual countries (China, India, Japan, United States of America, and Russia) and six aggregated regions formed by the remaining countries (European Union, Latin America, Sub-Saharan Africa, a combined Middle East / North Africa / Central Asia region, Other Asia, Rest of the World). Trade is explicitly represented for final goods and primary energy carriers. Macro-economic production factors are capital, labour, and final energy. The economic output is available for investments into the macro-economic capital stock as well as for consumption, trade of goods, and financing the energy system.

The macro-economic core and the energy system module are hard-linked via final energy demand and costs incurred by the energy system. Economic activity implies demand for the final energies electricity, non-electric energy for stationary end-uses and transport. These final energy demands are determined in a nested production function with constant elasticity of substitution (CES). The energy system module accounts for regional endowments of exhaustible primary energy resources (coal, oil, gas and uranium) and renewable energy potentials (biomass, hydro power, wind power, solar energy, geothermal energy). REMIND represents the build-up and vintaging of capacity stocks of more than 70 technologies that convert primary into secondary energy carriers or distribute these secondary energy carriers to end use sectors. The model accounts for the possibility of combining either fossil fuel or bioenergy use with carbon capture and storage (CCS). Since trees and crops extract CO₂ from the atmosphere, deploying bioenergy in combination with CCS (BECCS) leads to net negative CO₂ emissions. Learning-by-doing effects are explicitly represented via global learning curves for wind and solar technologies as well as electric vehicles. This implies that technology policies effectively lower future installation costs of the supported technologies in all regions. REMIND does not consider any hard limits on the expansion rate of new technologies. Instead, a cost mark-up ("adjustment costs") is applied that scales with the square of the relative change in capacity investments in order to mimic real-world inertias in technology up-scaling. This yields technology diffusion rates that are broadly in line with historical patterns. The retirement of fossil capacities before the end of their technological lifetime is possible, but limited to a rate of 4% per year.

Climate policies can be implemented as limits on greenhouse gas (GHG) emission budgets – as done in this study for the long-term climate policy – or as explicit carbon price trajectories that apply to all GHG – as done for the short-term policy. In both cases, full what-flexibility for mitigation exists and global warming potentials (GWP100) are used for the equalisation of prices across GHG species. Carbon price trajectories under budget policies emerge endogenously from the model and due to arbitrage effects show a yearly growth rate identical to the interest rate on endogenous capital investments in the model of 5-6 %. Consumer fuel taxes and subsidies are
represented as pre-existing policies impacting energy use. While in default settings, subsidies are assumed to be phased out linearly until the year 2050 and taxes are constant, the C&L policy scenarios foresee an accelerated subsidy phase-out and a convergence of transport fuel taxes. These apply on the final energy level, so that the effective tax rate per vehicle-km for electric vehicles is one third of that for vehicles powered by liquid fuels, given the higher tank-to-wheel efficiency of electric vehicles.

The REMIND model does not take effects of climate-induced damages into account, nor costs of adapting to climate change. Costs mentioned in the paper, such as consumption losses, therefore always refer to gross costs of reaching a mitigation target, assuming no costs of damages or for adaption.

**B. Detailed scenario results**

This section provides details about (i) the temporal trajectories of economic impacts in the different policy scenarios presented in the main paper, (ii) energy system impacts of technology policies until 2030, including inter-sectoral leakage effects, and (iii) short- and long-term economic impacts for the full set of policy scenarios considered in this study.

Fig. 1 illustrates the two-stage character of the policy scenarios of this study. With the exception of the two immediate scenarios (Opt), there is a distinct trend break in the year 2030, when the myopic period ends and the long-term target is adopted in all scenarios. In panel b), the implication of the long-term cumulative budget of 1500 Gt CO₂ from 2000-2100 becomes apparent, as scenarios with higher mid-term emissions have to compensate with lower emissions in the second half of the century. This has implications for inter-generational distribution of economic impacts as seen in panels a), c) and d). From panel c) the difference between the coal moratorium (CM) and the low-carbon support policies (LCS) after 2030 stands out: Unlike the LCS policies, the CM policies do not lead to electricity prices significantly lower than those in scenarios without technology policy (noT), as the ramp-up of low-carbon technologies has not been prepared before 2030 as in the LCS scenarios. Therefore, high cost mark-ups associated with the fast ramp-up of low-carbon technologies (see section A) after 2030 make the marginal electricity capacity additions more expensive, as reflected in the electricity price.
Figure 1: Temporal trajectories of global a) Carbon Price, b) GHG emissions, c) Average electricity price, d) Consumption loss and e) Coal price (without carbon price). The pricing dimension of the scenarios is represented with four different line colors and the different markers and line styles differentiate the technology dimension. Please note that the horizontal time axis spans until 2050 in the panels a, c, and e in the left column, and until 2100 in panels b and d in the right column. Throughout the whole paper and supplementary material, all monetary values are shown in constant 2013 prices. We used an inflator of 1.207 to convert the model-internal 2005 prices.
The impacts of the different combinations of sub-optimal pricing and technology policies are apparent in the generation mixes for electricity and non-electric fuels. Technology policies bring the electricity system closer to the optimal configuration (Fig. 2a). This effect is even more pronounced under a carbon tax. For the other fuels, the technology policies, which mostly target the electricity system (with the exception of biofuels with CCS and electromobility), lead to mixed results (Fig. 2b). Due to higher leakage effects (as discussed below), scenarios with cap-and-trade policies show greater differences to the optimal scenario.

Figure 2: Differences in global production of a) electricity and b) other fuels in 2030, differentiated by source.

Unlike a carbon price that impacts the whole economy, the technology policies have a sector-specific impact that can be seen in the sectoral coal use as depicted in Fig. 3: Optimal carbon pricing in scenario Opt-noT leads to a total decrease of 100 EJ of coal use relative to the sub-optimal carbon pricing scenario Tax-noT, with 60% in the power sector and 40% in the rest of the energy system. Both technology policies tend to decrease the use of coal in the power sector, while coal use increases outside the power sector. Two processes lead to this inter-sectoral leakage: The lower coal demand from the power sector leads to a lower global coal price (Fig. 1e). This implies that coal becomes more competitive for other uses. Additionally, in scenarios with cap-and-trade, the lower coal use in the power sector leads to a lower demand for CO₂ permits. This causes lower permit prices (Fig. 1b and Fig. 1 of the main paper) which additionally benefits the competitiveness of coal.

The Low-carbon support policies (LCS) do not target coal use directly, but mandate additional power generation from low-carbon technologies. In the scenario with a carbon tax, this leads to a small decrease of coal use for electricity generation, which is crowded out by the low-carbon electricity. In the cap-and-trade scenario, due to the additional permit price reduction effect, there is increased coal use even in the power sector, so that total coal use expands.

The coal moratorium (CM) leads to a decrease of coal use in the power sector of ~ 25 EJ. While in the tax scenarios the coal price effect leads to leakage rate of around 25% (i.e. one fourth of the coal...
saved in the power sector is used in other sectors), in cap-and-trade scenarios higher leakage rates are observed due to the additional effect via permit prices.

Figure 3: Differences in coal use with respect to the Tax-noT scenario (sub-optimal pricing implemented as tax and no technology policies) in 2030.

Complementing Fig. 3 of the main text, Fig. 4 shows the two economic short-term indicators for policy scenarios with carbon tax and different technology policies. The ranking of the different scenarios for both these indicators is identical to that in the long-term cost indicator, but the relative advantage of the LCS technology policy in comparison to the CM technology policy is more pronounced in the short-term indicators.

Figure 4: Economic indicators for the medium-term challenges of achieving the 2°C target after 2030. a) Maximum of decadal transitional consumption growth reduction in the period 2010-2050 and b) Maximum of decadal energy price increase in the period 2010-2050 (for definition and calculation of these indicators, see Luderer et al.² and section F).
The results in the four economic indicators for the full set of scenarios yield additional insights about the relative effectiveness of different policy packages (Fig. 5):

**Cap-CM vs. Cap-noT:** As a result of the high inter-sectoral coal leakage under cap-and-trade policies (see above), the coal moratorium policy does not mitigate the economic challenge in all four economic indicators. Short-term costs and the energy price increase are slightly higher in the Cap-CM scenarios than in the Cap-noT scenario.

**Zero-C&L vs. Tax/Cap-noT:** The results of a scenario without any pricing but the combined technology package (Zero-C&L) are comparable to scenarios with moderate carbon pricing but no technology policy (Cap-noT and Tax-noT). Due to non-existent pricing in the near-term, the Zero-C&L scenario even has a substantially lower cumulated carbon value. Nevertheless, the lack of any pricing policy is also a serious disadvantage of the Zero-C&L scenario as it implies that no experience with the implementation of carbon pricing policies is gained in the near-term.

**Tax/Cap-C&L vs. Tax/Cap-C&L**: In order to judge the complementarity of CM and LCS policies without the additional impact of subsidy phase-out and tax convergence, the scenarios Cap-C&L* and Tax-C&L* only combine CM and LCS without the additional tax and subsidy reform implemented in the C&L policy. With carbon tax, all indicators confirm the complementarity between the CM and LCS components, while this is not the case under cap-and-trade, as the permit price effect overcompensates the positive effects of the CM policy on the short-term cost and energy price increase indicators. The most significant difference between C&L and C&L* scenarios is observed in the carbon value indicator. The increased fuel taxes in the C&L scenarios lower the needed carbon price to reach the 2°C target.

**Tax-C&L vs. Tax-x2:** Tax-x1.5 and Tax-x2 are two additional scenarios with higher but still sub-optimal tax rates (50% and 100% higher, starting from 10.9 and 14.6$/t CO₂ in 2015 respectively) but without additional technology policies. From the comparison with the Tax-C&L scenario we find that the effect of the additional technology policies is comparable with that of a doubling of the carbon tax, although the effect on the different indicators varies.
Figure 5: Economic indicators for the long-term and medium-term challenges of achieving the 2°C target after 2030. 

- a) Cumulated discounted consumption loss relative to a baseline without any climate policy from 2010-2100
- b) Maximum of decadal transitional consumption growth reduction in the period 2010-2050
- c) Maximum of decadal energy price increase in the period 2010-2050
- d) Cumulated discounted carbon trade value from 2010-2100.

Please note that the relative size of the ranges of the y-axis differ from about 30% in panel a) to more than 300% in panel b). For definition and calculation of these indicators, see Luderer et al. and section F.

C. Impact of energy demand assumptions

The scenarios described in the main text all have the same underlying assumptions regarding autonomous energy efficiency improvements (AEEI), and the realised energy demand in the different scenarios only varies as a reaction to different prices.

To test the robustness of our results with regard to uncertainties regarding future energy demand trajectories, we analyse scenarios with high/low energy demand, realised by changes in the autonomous energy efficiency improvement rates. While with the reference energy demand assumption, final energy use in 2050 (2100) reaches 700 (990) EJ in reference scenarios without
climate policies, the low energy assumption results in 540 (560) EJ and the high energy demand assumption in 855 (1488) EJ. The global final energy consumption in 2012 was 374 EJ\(^{10}\).

The tax and cap sub-optimal pricing scenarios are constructed such that they yield the same emission quantities and prices in scenarios with reference energy demand assumptions and without additional technology policy (see Fig. 1 of main paper). This symmetry disappears if these cap-and-trade and carbon tax policies are applied to scenarios with varied energy demand assumptions (Fig. 6a). For scenarios with a cap-and-trade scheme, uncertainty about energy demand translates into uncertainty about the carbon price, with the low energy demand assumptions leading to a 2030 carbon price of only 2 US$/t CO\(_2\). A carbon tax shifts the uncertainty to emissions.

While difficult to model in our framework, dedicated policies for the implementation of efficient end-use technologies and behavioural change can lead to lower energy demand. The "low energy demand scenario" can thus be interpreted as a scenario with efficiency policies. While the costs associated with such demand-side policies cannot be assessed with our modelling framework, we can analyse the interaction of the lower energy demand assumption with the climate and technology policies. In such a scenario of combined demand- and supply side policies, the advantage of the carbon tax pricing mechanism in comparison to the cap-and-trade mechanism is even more pronounced than with reference energy demand (Fig. 6b).

### D. Description of technology policy packages

**noTech (noT):** No specific policies targeted at technologies are imposed in the period 2010-2030.

**Low-carbon support (LCS):** The adoption of six low-carbon technologies is imposed by global lower bounds with full where-flexibility as detailed in Table 22 and shown in Fig. 7.

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Table 2: Lower bounds on six low-carbon technologies imposed in the LCS scenarios.

<table>
<thead>
<tr>
<th>Technology</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaics (PV) [GW]</td>
<td>180</td>
<td>400</td>
<td>610</td>
<td>900</td>
</tr>
<tr>
<td>Concentrated solar power (CSP) [GW]</td>
<td>5.5</td>
<td>9</td>
<td>17</td>
<td>37</td>
</tr>
<tr>
<td>Wind power [GW]</td>
<td>506</td>
<td>826</td>
<td>1208</td>
<td>1647</td>
</tr>
<tr>
<td>Gas power with CCS [GW]</td>
<td>0</td>
<td>2</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Biofuel refinery with CCS [GW fuels]</td>
<td>0</td>
<td>2.4</td>
<td>18.5</td>
<td>84.5</td>
</tr>
<tr>
<td>Battery electric light duty vehicles [Mio. veh.]</td>
<td>0.6</td>
<td>3</td>
<td>10</td>
<td>27</td>
</tr>
</tbody>
</table>

For PV, CSP, Wind and electromobility, the bounds imply a continuation of the observed growth trends. For biofuels with CCS, the implied growth is similar to the past dynamics in the market for conventional biofuels (biodiesel and ethanol). Nevertheless, for all those technologies, policies will be decisive in determining whether such a continuation of the trends occurs or not. For Gas-CCS no suitable precedent for comparison is available. The comparison of the capacity bound in 2030 (50 GW) with the total installed gas electricity capacity in 2010 (1351 GW) illustrates that the needed policies can mainly consist of support for demonstration deployment.

The push for solar and wind is a support for increasing the market share for already mature but not yet fully economically competitive technologies. Therefore, we assume the excess deployment caused by the bounds to be financed by a premium fee on total electricity demand. This way, electricity prices for consumers increase (similar but not identical to the feed-in-tariff system in e.g. Germany, see Equation 1).

\[
p_r = \frac{1}{E^*_r} \sum_i (D^*_{r,i} - D_{r,i}) \cdot c_{r,i}
\]

with

- \( p_r \): premium fee levied on electricity consumption in region \( r \)
- \( E^*_r \): Total electricity consumption in region \( r \)
- \( D^*_{r,i} \): total deployment in region \( r \) for technology \( i \) in scenario with technology policy
- \( D_{r,i} \): total deployment in region \( r \) for technology \( i \) in scenario without technology policy
- \( c_{r,i} \): levelised cost of electricity (LCOE) for technology \( i \) in region \( r \)

The policies for electric cars and the two CCS technologies can be interpreted as demonstration deployment assistance, with none of these technologies exceeding 1% of the respective total market in 2030. Therefore, they are implemented purely as lower bounds in the model, which is equivalent to subsidies financed by the general public budget, depressing energy (service) prices slightly.
Figure 7: Comparison of recent historic evolution with the LCS lower bounds for five technologies. Historic data for panels a) - d) is from REN21\textsuperscript{12} and for panel e) from IEA\textsuperscript{13}. The numbers in black and red denote the maximum yearly growth as seen in the historical record and yearly growth between 2025 and 2030 implied by the bounds, respectively.

**Coal moratorium (CM):** This policy corresponds to a phase-out of the construction of coal-fired transformation plants. With the exception of 150 GW, representing the additions due to projects currently under planning and construction, no new freely emitting coal transformation capacity can
be built. Electricity, district heat, liquids, and gas generation based on coal can therefore only be expanded if combined with CCS. The only freely emitting usage for coal that is not limited by this policy is the direct use as solid fuel for residential heating and industry processes. The 150 GW of freely emitting coal power plants can only be built from 2013-2017 (20 GW per year) and 2018-2022 (10 GW per year) with full where-flexibility.

**Combined low-carbon push and coal moratorium (C&L):** This scenario combines the two policy packages as detailed above. Additionally, the phase-out of fossil fuel consumer subsidies is accelerated, with a linear decrease to zero subsidies in 2030 (all the other scenarios foresee the phase-out of subsidies until the year 2050). Furthermore, the taxation of transport fuels is harmonised across regions. Apart from Japan and Europe, whose higher taxes are supposed to stay constant, all regions' transport fuel taxes converge to a level of 12 US$/GJ or ~0.4 US$/litre in the year 2030. This level is higher than the current tax level in the US but lower than taxes in most European countries and Japan.

### E. Description of carbon pricing policies

**Short-term policies:** The definition of the sub-optimal carbon pricing policies is adapted from the AMPERE studies "high short-term target" scenario (HST)\(^{14}\). It represents a lenient interpretation of the Copenhagen pledges, with only the unconditional pledges being realised\(^{15}\). Due to computational advantages and given the symmetry of both control mechanisms in models like REMIND, the cap-and-trade scenarios (Cap) are actually implemented as tax runs with iteratively adjusted carbon prices, so that the prescribed 2030 GHG emissions target of 60.8 Gt CO\(_2\)eq is met. The resulting carbon price trajectory of the scenario Cap-noT with reference assumptions - reference energy demand, no technology policy - is used for all runs with a carbon tax (Tax), so that the scenarios Cap-noT and Tax-noT are equivalent. Although carbon prices tend to vary across models for identical climate targets, this tax trajectory is lower than CO\(_2\) prices in the immediate 450-fulltech-OPT scenario for all nine models participating in AMPERE. Furthermore, it is below the range of CO\(_2\) prices in optimal immediate mitigation scenarios in the AR5 database of 16-73 US$/t CO\(_2\) (This is the range of all scenarios categorized as climate forcing category 1, 1-2 or 2, policy category P1, technology category T0 and coming from “foresight” models able to compute intertemporally optimised scenarios)\(^{16,17}\).

We differentiate between a pure tax and a pure cap-and-trade scheme, to work out the fundamental differences in the interaction with other policy instruments. Note that different hybrid pricing mechanisms like a cap-and-trade system with a price corridor or a carbon tax with an emission feedback on the carbon price trajectory\(^{18}\) are being discussed in both academia and the policy arena. A cap-and-trade scheme with a price floor can in principle yield equally positive interactions with technology policies as the carbon tax we study, so that our finding should not be misinterpreted as indicating a universal superiority of a carbon tax. As argued by Goulder and Schein, ‘specifics of design’ of the chosen instrument ‘may be as important as the choice between the two instruments’.\(^{19}\)
**Long-term policy:** The long-term climate policy is defined as a limit on the cumulative 2000-2100 CO₂ budget of 1500 Gt CO₂. In order to achieve the equivalent pricing of non-CO₂ emissions, this policy is implemented in the model as a limit on the global cumulative GHG budget. This GHG budget is iteratively adjusted so that the required CO₂-only budget is met.

**F. Definition of economic indicators**

The four indicators shown in Fig. 3 and 4 of the main text and in Fig. 4 and 6b of this supplementary material are adapted from a previous study². The supplementary material of this study contains a detailed description of the calculation for each of these indicators. Here we use these indicators with two slight modifications: we show the energy price increase indicator without the baseline price increase subtracted (see Equation 4 below), so that the values reported here are slightly higher than in Luderer et al². Energy prices in REMIND increase even without climate policies due to economic growth and the represented scarcities of energy supply, both for fossil fuels and renewables. Secondly, the long-term costs indicator is normalized by consumption instead of total output (see Equation 2), which also leads to higher values.

Whereas the traditional indicator for assessing mitigation challenges has been the cumulated consumption loss (referred to in the main text as **long-term costs** (LTC, see Equation 2)), other measures might be more meaningful for assessing the institutional and political requirements of mitigation²²⁰. One reason is that the accumulation procedure for consumption loss masks changes in the temporal profile of the mitigation burden. Delayed scenarios imply lower costs in the near-term and higher losses in the long-term, which means that there is a much quicker increase of those costs in the transition time. This is captured by the **short-term costs** indicator (STC, see Equation 3), measuring the maximum transitional consumption growth reduction over a decade.

\[
LTC = \left( \sum_{t=2010}^{2100} (C_{Baseline} - C_{Pol}) \cdot (1 + \delta)^{2010-t} \right) / \left( \sum_{t=2010}^{2100} C_{Baseline} \cdot (1 + \delta)^{2010-t} \right) \cdot 100\% \tag{2}
\]

\[
STC = \max_{2010 < t < 2050} \left( g_{Baseline}(t) - g_{Pol}(t) \right) \tag{3a}
\]

\[
with \quad g(t) = \left( C(t + 5a) / C(t - 5a) - 1 \right) \cdot 100\% \tag{3b}
\]

with \( C \) Consumption
\( \delta \) discount rate (5% used here)
\( g \) Growth rate of consumption

On the other hand, the overall costs to society might not be decisive, especially as long as they do not exceed 5% of overall wealth. At this low level, it might be the distributional issues that play a much bigger role, as they can result in much higher relative losses for certain population groups. A rigorous assessment of distributional issues would require modelling the interaction of different income groups, which none of the detailed long-term energy-economy-climate models is able to do for computational reasons and lack of solid knowledge about long-term drivers of inequality. The pragmatic alternative proposed by Luderer et al² and followed here is to use the maximum energy price increase (**EPI**, see Equation 4) and the total carbon value (**CV**, see Equation 5) as proxies to
assess the institutional requirements for balancing the distribution of costs across income groups and countries.

\[ EPI = \max_{2010 < t < 2050} \left( g_{EPX,Pol}(t) \right) \]  
(4a)

with \( g_{EPX}(t) = (EPX(t + 5a) / EPX(t - 5a) - 1) \cdot 100\% \) \( (4b) \)

and

\[ EPX(t) = EPX(t - 5a) \cdot \sum_r \sum_i p_{ir}(t) FE_{ir}(t) / \sum_r \sum_i p_{ir}(t - 5a) FE_{ir}(t) \]  
(4c)

\[ CV = \sum_{t=2010}^{2100} p_{CO2}(t) \cdot E(t) \cdot (1 + \delta)^{2010 - t} \]  
(5)

with \( g_{EPX} \) Growth rate of the energy price index  
\( EPX \) Chained energy price, \( EPX(2010) = 1 \)  
\( p_{ir} \) Price of final energy carrier \( i \) in region \( r \)  
\( FE_{ir} \) Use of final energy carrier \( i \) in region \( r \)  
\( p_{CO2} \) Carbon price  
\( E \) Sum of all positive greenhouse gas emissions, excluding negative emissions from BECCS

**Comparison with previous studies:** So far, cumulative consumption loss was the most widely used metric for assessing the socio-economic implications of mitigation scenarios. In this metric, the results of the REMIND model lie within the interquartile range reported in the latest IPCC report\(^2\) (compare the dark blue boxes in the right panel of Figure TS.12 with Figure 1c in this supplementary material). The other three metrics have so far not been studied in broader assessments. The only available comparisons with other models are therefore single studies analysing the growth reduction parameter and the carbon value. REMIND results in the growth reduction metric are very close to those of the WITCH and GCAM models and higher than for the MESSAGE model\(^2^0,^2^2\). The response of this indicator to a delay in climate policies is very similar in all four models. For the carbon value, regional results from REMIND are very close to the median of 8 models in the EMF 27 study\(^2^3\), with the exception of the region of reforming economies.

**References**

Chapter 7

Synthesis and Outlook

This final chapter contains an overall discussion of the research presented in the five preceding chapters. First, Section 7.1 offers short summaries of the results of each of the research chapters. Second, an overarching discussion along the three main research questions including implications for policies follows in Section 7.2. To conclude, Section 7.3 discusses the methodological limitations that have to be kept in mind when interpreting the results and Section 7.4 presents suggestions for future research that builds on our work.

7.1 Summary of Results

Chapter 2: Economic mitigation challenges: how further delay closes the door for achieving climate targets

This chapter explores the lower limit of achievable climate targets and their dependency on technology availability and timing of policy implementation. With an early start of comprehensive climate policy before 2020 and full technology availability our assumptions on tolerable costs in four considered economic metrics imply a lower limit of achievable temperature stabilization targets of $\sim 1.7^\circ$ C. This means that much of the room to accommodate the $2^\circ$ C target has already been consumed.

The analysis of a detailed scenario set has shown that the trade-off curves between costs and target stringency are highly convex, i.e. mitigation costs increase disproportionally with increasing target stringency. This result holds for all four considered cost metrics and all different assumptions on technology availability and policy delay. If bioenergy combined with CCS (BECCS) is available, the convexity is somewhat less strong for targets defined as 2100 temperatures than for targets defined as maximal temperatures, as a temporary temperature overshoot can be compensated by negative emissions. Both a delay of stringent policies as well as the unavailability of crucial technologies like CCS, biomass or renewables shift the trade-off curves towards higher costs and/or temperatures. On the other hand, lower exogenous assumptions on the demand for energy services and final energy results in slightly lower costs and/or temperatures. A continuation of weak climate policies inevitably increases the risk of exceeding the $2^\circ$ C threshold and returning
to 2 °C in such a scenario will require large-scale deployment of BECCS at the end of the century.

The chapter demonstrates that transitional indicators like short-term consumption growth and energy price increases as well as the value of carbon are more sensitive to a delay of climate policies. Therefore, although stringent climate targets might still seem achievable after a delay until 2030 in technical and economical terms, it might be the institutional requirements to balance the distributional impacts of rising prices and created rents that put limits to the mitigation actions that can be performed in such scenarios.

Chapter 3: Implications of weak near-term climate policies on long-term mitigation pathways

This chapter has shown that the level of ambition implied by current regional mitigation pledges is insufficient to stabilize GHG concentrations over the 21st century. In scenarios following such policies, emissions in all three considered models peak around mid-century and return to roughly current levels toward the end of the century. All three models are able to meet a stringent 2 °C target after following the moderate policy trajectory until 2030. Such a delay however exacerbates the challenges of meeting this target, as reflected in higher carbon prices, faster decarbonization rates, temporary depressions of energy demand and a higher amount of stranded assets resulting from the early retirement of transformation capacities based on fossil fuels. The bulk of mitigation action is contracted to the first two decades after adoption of the stringent target which reduces income growth markedly in these decades in all three models. Even though the absolute level of aggregate mitigation costs differs considerably across the models, the relative increases due to the delay and the impact on the income growth are very similar across the three models.

Chapter 4: Carbon lock-in through capital stock inertia associated with weak near-term climate policies

The comparative analysis of scenarios with moderate policies until 2030 across nine models has identified a number of crucial model differences as well as some robust results. The excess emissions during the time of moderate policies, i.e. the emissions that would not occur under hypothetical optimal policies, vary in size, as optimal emission levels in 2030 vary across models. Regarding their composition, however, the biggest share in all nine models stems from coal-fired electricity generation. The suboptimal deployment of low-carbon alternatives is another robust feature, although the importance of different low-carbon fuels varies across models. To compensate for near-term excess emissions, the demand side emissions – most of which come from the transport sector, in the second half of the century have to be reduced further in models able to meet the 2 °C target. On the other hand, different model assumptions related to the early retirement of fossil capacities, the ramp-up of low-carbon technologies, and the long-term availability of negative emissions to compensate for higher positive emissions lead to different emission outcomes in the two decades following the adoption of stringent climate policies. While some models show higher inertia in all or some of the emitting sectors, other models are more flexible with respect to a swift change of emission dynamics.
The complementary analysis of scenarios with lower energy demand assumption has shown that the greater flexibility implied by a lower energy demand leads to considerably reduced mitigation challenges in most models. On the other hand, due to the specification of the moderate short-term policy as a yearly emission limit, some more specific challenges are even exacerbated. Quite intuitively, the lower energy demand results in less reduction of the carbon intensity, especially for electricity. In some models, the amount of coal-base power generation capacities that have to be retired after 2030 therefore is equal to the case of reference energy demand or even greater.

Chapter 5: Long-term climate policy implications of phasing out fossil fuel subsidies

Our results confirm the moderate short-term emission reductions of around 5% resulting from a complete phase-out of fossil fuel consumer subsidies as found by previous analyses with ENV-Linkages and the World Energy Model. We however put this result into the long-term context, showing that – absent dedicated climate policies – emission levels return to the level with subsidies towards the end of the century. Whereas in the short-term, leakage across regions only plays a minor role, the reduced demand for fuels in regions phasing out subsidies lead to lower resource prices. Therefore, the competitiveness of renewables is compromised and especially the use of solid coal becomes economically more attractive, leading to a small coal renaissance in our scenarios. The positive environmental effect of a phase-out of subsidies can only be harnessed if complementary policies like carbon prices and technology policies tackle these potential adverse side-effects.

Regarding the regional welfare effects of a subsidy phase-out, we find very mixed results and identify the different channels for gains and losses. Regions abandoning subsidies gain through a small efficiency effect. For exporters, a unilateral phase-out is beneficial as more fuels can be exported. Under more universal subsidy phase-out policies, however, resource prices drop, thus overcompensating any gains from increased export volumes. On the other hand, importers benefit from lower prices.

Chapter 6: Complementing carbon prices with technology policies to keep climate targets within reach

This chapter has found that the combination of a moderate carbon price floor with a mix of technology policies can keep ambitious climate targets within reach at moderately increased costs compared with the optimal immediate policy. In comparison with only a moderate carbon price, the gap in aggregate costs with respect to the optimal benchmark is half-way closed and the total carbon value is even lower than in the optimal benchmark. This shows that there is a trade-off between efficiency as measured with the aggregate costs on the one hand and the distributional impacts and institutional requirements as measured in the value of carbon on the other hand.

The research has shown that the beneficial effect of technology policies is much greater if the carbon pricing is implemented with a price floor. This is because in a pure cap-and-trade system the additional technology policies lead to a lowering of permit prices which increases the emissions rebound or leakage effect of emission mitigation resulting from technology regulation. Furthermore, the study has demonstrated that policies regulating the most polluting technologies and policies supporting low-carbon alternatives are highly
complementary. The reason is that natural gas acts as a buffer so that the effect of each policy type cannot be produced as a side-effect by the other policy. As an example, a coal moratorium results in higher electricity generation from natural gas instead of a higher renewable deployment.

7.2 Discussion

7.2.1 Economic Implications of a Delay of Stringent Climate Policies

One of the central contributions of the research presented in this thesis is to inform policymakers about the implications of sub-optimal near-term policies. The discourse prior to our work centered on the amount of excess emissions in the near term relative to a hypothetical optimal climate policy approach with comprehensive action starting immediately, the so-called emissions gap as depicted in Figure 1 (Rogelj et al., 2010, 2011; den Elzen et al., 2012). As also seen in our work (Chapter 4), this gap cannot be quantified precisely even for a given global near-term emissions target, as the counterfactual optimal emission trajectory depends on many uncertain parameters and assumptions and therefore varies from model to model. The emissions gap is also a function of when it is evaluated. For example, the current 2020 emissions gap is smaller than the one derived in 2010, simply because optimal pathways starting now have higher 2020 emission levels than optimal pathways that started in 2010. In several instances the emissions gap concept has been misinterpreted to imply that the 2 °C target becomes unachievable unless the gap is closed. Statements about the feasibility of a particular climate target, however, require a rigorous evaluation of the economic implications of higher-than-optimal near-term emissions. Such evaluations require an analysis of two-stage scenarios (see Figure 1) as developed for this thesis.

Our analysis of these scenarios has shown that the traditional metric for evaluating the welfare effects of policies, consumption losses aggregated over a long time horizon, is an insufficient indicator for the challenges implied by delayed climate policies. These consumption losses show a slight increase the longer stringent action is delayed (Chapters 2 and 3). If additionally the availability of crucial technologies is restricted as done in Chapter 2, costs increase even more and stringent targets are rendered infeasible (Section 7.3) in many models (Riahi et al., 2015). Despite this, we have shown that detailed, more policy-relevant indicators (for a discussion see Section 1.3.5) show higher relative changes than aggregate costs already at shorter delays and with full technology availability. Chapter 3 has shown that decadal reductions of income growth are more than doubled by a delay of 20 years, which is a robust finding across three models. Chapter 2 additionally has found steep increases in two indicators that are especially relevant for evaluating the distributional and institutional challenges of climate policies, namely energy price increases and the total value of carbon. It is noteworthy that the aggregate indicators mask the important issue of intergenerational distribution: while delaying climate policies avoids costs in the near term, it puts a much higher economic burden on the energy system and societies in later decades if stringent climate targets are still to be achieved.
All these findings imply that it is imperative to increase the ambition level of current climate policies to a level consistent with long-term targets if the costs and distributional impacts are to be minimized. The innovative scenario framework in Chapter 2 offers a complementary way of illustrating the effect of a delay, analyzing the difference in achievable temperature for a given willingness to pay instead of the cost increases for a given temperature target. It shows that a delay of stringent policies by 15 years implies that the lowest temperature target that can be achieved at a given level of economic burden is shifted 0.2-0.4 °C upwards, thus effectively closing the door for the target of limiting global warming to no more than 2 °C.

From the observation that the alternative indicators show higher decreases with delay it can be argued that policymakers should put more focus on the distributional implications and institutional requirements of climate policy. Even if the high carbon prices required to reach climate targets are unlikely to materialize in the immediate future, policymakers should already now work on and test institutional mechanisms to administer higher carbon value flows in the future, e.g. by emission verification mechanisms in a cap-and-trade or carbon tax scheme. Furthermore, policies to balance distributional impacts of higher energy prices and the simultaneous devaluation of fossil resources and appreciation of carbon emissions (Bauer et al., 2013) will be needed in the future.

The knowledge about the implications of a delay of climate policies is useful in several different ways. One is the ability to trade off costs and risks arising from the delay with the opportunity costs of enabling stringent policies now. In this sense, the finding of transitional short-term costs that increase sharply with a policy delay help to illustrate the urgency of acting fast in a very transparent way. Another benefit of understanding the implications of a delay is that it helps to develop strategies for addressing its worst consequences with targeted measures. The preceding paragraph followed this rationale, applied to the findings about differences in the four analyzed metrics, as discussed in Chapter 6 and Section 7.2.3. Further concrete consequences can be drawn from the analysis of the energy system that follows.

### 7.2.2 Energy System Implications of a Policy Delay

We have found that the delay of stringent policies not only leads to higher emissions, but also results in continued investments into carbon intensive infrastructure like coal-fired power plants that make deep emissions cuts after implementation of stringent policies more difficult. From the comparative analysis of a wide range of models it is a robust insight that most of the excess emissions occur in the electricity sector, with a large share stemming from coal. Previous studies of optimal mitigation scenarios have already identified the power sector as the main venue where fast and deep emission cuts are easiest to achieve (Kriegler et al., 2014; Krey et al., 2014). Our analysis thus demonstrates how a delay of policy implies that the ‘low-hanging fruit’ of rapid power sector decarbonization is forfeited. This is especially problematic, as most of the infrastructure in the power sector has long construction and life times, implying that very rapid changes as foreseen in some delayed action scenarios will be difficult to achieve.

One critical aspect of this inertia is the possibility of retiring whole fleets of mainly coal-fired power plants before the end of their technical life time. In scenarios that allow for
such retirement, large capacities are immediately shut down after adoption of stringent policies, with severe implications for the investors of such assets. In scenarios without retirement possibility, additional emissions from such plants have to be compensated by negative emissions in the future and in many scenarios, stringent targets after prolonged delays of policy become infeasible. An option only represented in a few models but worth considering for policymakers is the retrofitting of plants with carbon capture and storage (CCS) after implementation of stringent policies (Johnson et al., 2015). This requires special plant designs already during the initial construction. Therefore policies that prescribe such designs for newly built plants in combination with R&D support for CCS could be an alternative policy approach for countries not willing to implement a more stringent coal moratorium.

Another necessary condition for the quick retirement of large amounts of fossil capacities after adoption of stringent policies is that alternative generation can be brought online fast enough. Although delayed scenarios often exhibit a short-term depression of energy demand shortly after adoption of the stringent policy, the quantities that have to be installed in only one or two decades are immense (Eom et al., 2015). To what extent such a rapid ramp-up of technologies can be realized is uncertain, especially if it is not prepared for during the period of moderate policies. Studies comparing the projected ramp-up of technologies in the future with past experience have so far only considered idealized policy scenarios (Wilson et al., 2012a), confirming the plausibility of the apparent ramp-up rates of such scenarios.

Beyond the inertias on the supply side that are generally represented in the models, other inertias related to the distribution and consumption of energy might make fast decarbonization after a period of moderate policies even more difficult, for example in the transport sector (Guivarch and Hallegatte, 2011). Therefore the finding that the decarbonization happens in a much shorter time frame in delayed policy scenarios indicates a considerable challenge for many sectors.

The achievement of stringent climate targets after prolonged periods of only moderate policies not only requires very fast decarbonization rates (Riahi et al., 2015), but also a considerable amount of negative emissions through BECCS in the second half of the century. This is a worrying finding, as it implies that a failure to develop this so far unproven technology would result in a failure to meet the long-term target with only moderate policies for the next one or two decades. Chapter 2 quantifies the difference in 2100 temperature for scenarios with or without BECCS to be close to 0.5 °C. This implies that research and demonstration projects for both CCS and second generation biofuel production are urgently needed in order to improve the understanding about the long-term risks and potentials of these technologies.

7.2.3 Portfolios of Climate Policy Instruments to Mitigate the Adverse Effect of a Delay of Stringent Climate Policies

The work presented in this thesis offers important conclusions about the role of policy instruments and their combinations. If a globally and sectorally uniform high carbon price is not possible to implement – which seems to be the case at least for the near future – a well designed combination of different instruments can still initiate important transfor-
mation dynamics. The portfolio we have found to perform best combined an increasing carbon tax, support for key low-carbon technologies, a ban on the construction of freely emitting coal transformation plants and a reform of fuel taxes and subsidies. In such a policy mix, complementary technology policies substantially enhance the effect of moderate carbon prices. The optimal benchmark policy of a high uniform carbon price still outperforms such a policy mix in terms of aggregate efficiency, but we have shown that this superiority does not hold in all indicators. Judging from the high number of enacted technology policies, we can expect that the policy portfolio approach has the advantage of lower barriers to political implementation. It can also result in a lower aggregate value of carbon. Thus the institutional requirements for administering the verification of emissions and for distributing the costs and revenues of carbon pricing are reduced.

The positive impact of a complementary technology policy in a specific sector could, however, have negative side-effects in other sectors that reduce the overall effectiveness of such a measure. We have shown that in order to minimize such undesired side-effects, also referred to as emissions rebound or leakage in the economic literature, a fixed carbon price floor should be in place. In this situation, emission rebounds can still occur via depressing effects on resource prices but the negative effect of a decrease in permit prices is avoided. This finding should, however, not be interpreted as a general superiority of a carbon tax policy over a cap-and-trade scheme. If a relevant and rising price floor in the form of an auction reserve price is implemented into a cap-and-trade scheme (Pizer, 2002), such a hybrid scheme could work similarly well and might have advantages in other characteristics not considered here (Goulder and Schein, 2013). The opposite form of a hybrid, a carbon tax scheme that leads to the achievement of a certain emissions target through a feedback of past emissions on future tax rate increases, has also been proposed (Metcalf, 2009).

The detailed analysis of scenarios with technology policies regulating very dirty technologies and policies that support low-carbon alternatives has shown that such policies have complementary effects. Unlike what basic intuition could suggest, each of these policies alone does not lead to the obsoleteness of the other as a side-effect. The reason for this is the very flexible intermediate energy carrier gas. If only coal is banned, gas is the currently cheapest option to replace it. And if renewables are pushed into the electricity sector, gas rather than coal generation is reduced the most, as can also be seen from the current German example. With respect to the exact implementation of technology policy, our study has taken an agnostic stance. Due to our model framework, we were unable to differentiate between instruments such as production subsidies like feed-in-tariffs or tax breaks, portfolio standards or performance standards. This is in our view not a disadvantage, as in a second-best setting that we represent, various approaches will inevitably be pursued in different countries, adapted to local circumstances and political preferences. Therefore our results should be used to estimate the potential of technology policies if implemented successfully and at the global scale. It is clear that poorly designed support policies will not yield the low-carbon up-scaling assumed here, or could become overly costly to government budgets or consumers if they create excessive wind-fall profits not considered here.

Another conclusion that can be drawn from the analysis of technology policies is that in a portfolio policy approach having a multitude of targeted policies is beneficial. The basic logic of this policy approach is to employ a moderate carbon price that acts throughout
the economy, while additional regulation targets the most crucial sectors and technologies. We have seen that such regulation, for example the ban of new coal-fired power plants, leads to lower coal resource prices as a side-effect. This in turn makes coal use more attractive in sectors not subject to targeted policies, such as coal use in industry applications or for residential cooking heating. Therefore additional policies that target these sectors could lead to further emission reductions and further preparation of the energy system transformation. The latter example, regulating coal use for residential cooking and heating, has the further benefit that it is highly concentrated regionally to China and would yield substantial health co-benefits (IEA, 2011, Chapter 13).

Subsidies to fossil fuels in 2013 amounted to $548 billion (IEA, 2014, Chapter 9). They are problematic, both environmentally since they encourage wasteful consumption, as well as economically since they burden public budgets. Chapter 5 has shown that the rapid phase-out of these subsidies has a near-term environmental benefit as well as economic benefits for many regions. From a climate policy perspective, it is however important to stress that such a phase-out by itself does not have a lasting positive impact on mitigation efforts. Due to the resource-price depressing effect, it could even lead to a comparative disadvantage of some low-carbon alternatives, slowing their integration into competitive markets. Therefore, combining a subsidy removal to other policies such as carbon pricing, technology support and fuel taxes as demonstrated in Chapter 6 seems most promising. Especially for developing countries, the removal of subsidies and introduction of carbon prices and fuel taxes must be undertaken with careful consideration of distributional effects. Regressive effects that further aggravate poverty problems should be avoided. Interestingly however, and contrary to common wisdom, transport fuel taxes are often progressive in very poor countries (Somanathan et al., 2014, Section 15.5.2.3).

The work in this thesis has represented near-term climate policies either as one instrument in a regionally differentiated fashion (Chapters 2 and 3) or as a multitude of instruments in a globally uniform way (Chapter 6). The unfolding reality of climate change mitigation policies will probably consist of a regionally fragmented map of jurisdictions with a multitude of policy instruments each. I would argue that such a fragmentation in the early phase – and given the long time horizon of the problem we are still in the early phase of the human history of climate change policies - is not only a problem but also has the following advantage: It allows for multiple experiments of which instruments work best and furthermore allows for the adaptation to country-specific circumstances. The crucial question is, however, how different countries can coordinate their ambition level in such a fragmented mode so as to avoid free-riding problems. The currently pursued form of “intended nationally determined contributions” without any form of institutionalized comparative assessments of stringency level does not seem optimal to incentivize a race to the top. A promising way forward could be to concentrate negotiations more on the comparison of minimal carbon prices (Weitzman, 2014) and technology expansion targets than on emission targets alone. Whether or not the direct linking of carbon markets offers more benefits or caveats at this stage is, however, rather questionable (Green et al., 2014).

Our work also contributes to the debate about the usefulness of the 2 °C target for guiding the climate policy discourse (Geden and Beck, 2014; Victor and Kennel, 2014). On the one hand, our analysis makes it clear that one needs a defined long-term target to be able to quantify the relative merits of different policy proposals for the short-term. According to one of our findings (see Chapter 6), only looking at short-term emission trajectories,
e.g. by quantifying an emissions gap, does not convey the full story. The task for the next two decades is not only to bring down emissions but also to prepare much deeper emission cuts in subsequent decades, which is similarly important. Only the analysis of long-term scenarios with specified targets can inform about the potential of specific policy instruments to bring about this preparedness. On the other hand, our work also makes it very clear that one needs to translate such a long-term target into more tangible short-term targets. This is complicated as there is no one-to-one relationship between short-term and long-term targets. The goal of limiting global warming to no more than 2°C above pre-industrial levels can be reached via different routes, differentiated through different sets of actions to be taken now and different costs and risks borne now and in the future. Nevertheless, different milestones - in terms of emission levels, emission peaking per country or globally, carbon prices, technology developments, etc. – should be defined as part of the international negotiations. They would, however, clearly be subordinate to the more aggregate targets like the 2°C target. Their role would be to act as “vital signs” (Victor and Kennel, 2014) that show whether or not the world is on track as a whole or per region to keep the long-term target within reach.

7.3 Limitations

The quantitative analysis of the impact of future policies is a difficult scientific endeavor. This is especially the case when no historic precedents for the same policies exist, as modeling is then the only quantitative tool to employ. This section has the role of giving a short overview of some of the specific shortcomings of the model-based analysis of climate change mitigation strategies that are relevant for the interpretation of the results presented in this thesis.

Economic Analysis

First of all it should be noted that economic analysis is not the only component of a comprehensive policy analysis. Various factors cannot reasonably be included into economic valuation such as rights, duties, social and cultural norms and values. These play an important role in policy discourses and decision making (Kolstad et al., 2014), implying that the role of economics is complementary to these other considerations.

There is no single correct way of doing economic analysis. Rather, for any quantitative evaluation a series of implicit or explicit normative decisions have to be taken (Edenhofer and Kowarsch, 2014). In our context, one example is the basic driving mechanism of the model. In the case of REMIND, it is a traditional neo-classical growth model. One of the implications of this choice is that in such models climate policy intervention always results in welfare losses compared with a no-policy baseline (and not taking damages of climate change into account). In the real world, it is conceivable that pre-existing inefficiencies could be alleviated as a side-effect of climate policies, leading to overall welfare gains instead of losses. One example for a model that incorporates such inefficiencies is the E3MG model (Köhler et al., 2006).

Similarly, the valuation underlying quantitative welfare analyses of future economy pathways is a very important choice that itself is very difficult to judge. Behavioral aspects
play a role here, for example preferences with respect to different types of energy services and energy carriers. Although it should be very clear that preferences do change over time and are doing so with a certain dependence on circumstances, comparative economic scenario analysis can in principle only compare scenarios with one set of assumptions on the evolution of preferences.

**Model Intercomparison**

A related fundamental problem of economic models is that there is no way of verifying them in a rigorous sense, due to the fact that human decision making cannot be predicted to the extent of natural systems that are subject to natural laws (Oreskes et al., 1994). Nonetheless, various approaches for increasing confidence into the robustness of results can be adapted from the scientific communities working on modeling of natural or technical systems (Schwanitz, 2013; Tol, 2014). Implicitly, the combination of model intercomparison studies (see Section 1.3.4) with recent efforts to classify models into different categories (Kriegler et al., 2015) goes a step into the direction of operationalizing the uncertainty about human behavior. The problem with the approach of aiming at a more comprehensive understanding by comparing results from different models is the completely unstructured, relatively random selection of models. Structured variations of parameters and model mechanisms in one modeling framework would be more straightforward to analyze and interpret but fail due to the disproportionately increasing workload of keeping many submodules compatible to each other. Therefore this thesis employed model intercomparison as the primary, yet imperfect means for evaluating the robustness of findings, and at the moment it seems unlikely that the community has a new solution to this problem soon. On the upside one can at least assert that the most basic fallacies like averaging results or the selection bias (Tavoni and Tol, 2010) have been recognized as such and therefore become less frequent in the literature.

The issue of selection bias has to do with the notion of “feasibility” and “infeasibility” of scenarios in a certain model and this also proves to be a problematic concept, as the term is used with different meanings. A straightforward but not always useful definition of infeasibility is when a certain scenario leads to numerical infeasibilities in the equation system of a model. Then, however, the question is how to deal with scenarios that are feasible following this definition, but have features that clearly are beyond plausibility, like for example an immediate jump of the carbon price to values of several thousand US$.

A completely unrelated potential drawback of model intercomparison is the long-term impact it has on the modeling work of the teams involved. The pressure to defend outlier results can lead to a tendency for "middle-of-the-road" behavior, so that the full range of uncertainty might not be fully represented in results of all available models. If, as in Chapters 3 and 4, key driving forces like GDP or population are harmonized across models before comparison, this artificial reduction of apparent uncertainty is clear. Such harmonizations nevertheless are useful to get detailed insights about specific processes, but it should be made clear that the relatively good agreement in variables such as baseline emissions is due to such harmonization procedures.
REMIND

Despite our efforts to explore second-best scenarios with respect to short-term policy stringency, the REMIND model still operates under a series of strong assumptions regarding the perfect response of the energy-economy system to policies. It calculates a central planner optimum, tantamount to perfect investment decisions under perfect foresight. An especially strong consequence of this is that the learning externality of technologies whose investment costs decline with cumulative deployment are internalized without policy intervention. Furthermore, the regions are assumed to fully cooperate so that the spill-overs of the learning externalities are internalized as well. All these assumptions are a conscious choice and fit to the purpose of the REMIND model in our work, namely to calculate efficient benchmarks that demonstrate the potential of certain policies.

Other simplifying assumptions in the REMIND model are, by contrast, rather due to the fact that more elaborate representations are not feasible computationally or due to the lack of understanding of relevant dynamics in the long-term. Examples are the relatively coarse spatial and temporal resolution as well as the representative household assumption that makes it impossible to directly analyze welfare effects across income groups of the considered policies. On the other hand these simplifying assumptions allow for a rather generic representation of policies, such that the discussion can be focused on the interactions of different technology and carbon pricing policies, separating it from the question about the best design elements of a particular technology policy.

Cost-Effectiveness Analysis

As mentioned in Section 1.2.1, the advantage of CEA – and the reason why it is employed here – is that the analysis is uncoupled from the potentially dominant and very uncertain issue of damage quantification. This has however also serious drawbacks. Past emissions have already locked the earth system into a considerable amount of future warming with resulting risks and costs. On the other hand, the policy instruments and technology deployment necessary for climate change mitigation also entail costs and risks. In the long run, after the understanding of both these categories of costs and risks has improved, a comparative assessment weighing costs and risks of both categories off each other will be needed for making informed choices.

A more concrete short-coming of CEA has been identified by Blanford (2013). Implicitly, CEA can be interpreted as a CBA with a very stylized damage function: Zero damages until a certain threshold, e.g. a temperature increase of 2 °C, with infinite damages beyond that threshold. If the climate target is formulated in terms of a constraint on 2100 temperature, radiative forcing or cumulative greenhouse gas budget, thus allowing for temporary overshoot, the infinite damage only applies at the end of the century. In case of cumulative emissions budgets as used in Chapters 4 and 6, temporary overshoots are allowed as long as they are compensated for by negative emissions later on and as long as the overall budget limit is complied with. Importantly, Blanford (2013) has shown that the assumptions on the availability of negative emission technologies in such a setting have a much different effect than under CBA where damages are accounted for along the full temporal trajectory. In CBA, a higher potential for negative emissions means that the aggregate mitigation cost curve is lowered, leading to a lower optimal temperature outcome. In terms of total emission trajectories, this mainly leads to lower emissions at the
end of the century when the technologies are employed. In CEA to the contrary, the effect of a higher potential of negative emissions is quite different. As the target to be achieved is fixed, higher potential for negative emissions cannot lower total cumulative emissions. If some or all of the potential for negative emissions is used, it is fully compensated by an equal amount of additional positive, fossils-based emissions. In intertemporally optimizing models, it is optimal to use much of the headroom for fossil emissions during the early decades of the century, whereas the negative emissions due to technology scale-up times mainly occur at the end. As a result, total emissions at the beginning are higher than without the additional negative emissions potential, compensated by higher negative emissions in the long term. This dynamic is at the core of the differences between the GCAM model with very large potential for negative emissions (see Supplementary Figure A1, Chapter 4) and the other models in Chapter 4, questioning the comparability of mitigation pathways with equal greenhouse gas budget, but large differences in negative emissions potentials.

An example for a more meaningful analysis of the merits of negative emissions potentials is the analysis performed in Chapter 2. There we show that not having BECCS available does have a much bigger impact on achievable 2100 temperatures than on the maximum of the temperature increase. An even higher potential for negative emissions than assumed in Chapter 2 would lead to even higher differences between maximum and 2100 temperature increase.

### 7.4 Suggestions for Future Research

The previous section has identified a series of limitations of the state-of-the-art of prospective model-based policy analysis. Most of these more fundamental limitations cannot be overcome easily. In this section, I want to give a short account of promising extensions of the present research that seem to both be doable and potentially offer a richer understanding.

One direction is to combine the regional differentiation of policies (Chapters 2 and 3) with the differentiation of policy instruments (Chapter 6). One drawback is that the number of different possibly options increases strongly in such a setting. Therefore, a structured selection of specific instruments per region will be important. The more it becomes clear that specific regions choose a particular instrument for enacted policies, the easier this task will get. So far, the United States are a clear candidate of a region that seems to be bound to rely on targeted sector-specific instruments instead of economy-wide carbon taxes or cap-and-trade schemes. In most other regions, a combination of moderate pricing schemes with incomplete sectoral coverage and technology policies seems most likely. A potential danger of only pursuing this kind of “realistic” research lies in the potential feedback of policy analysis on policy making: If the analysis exclusively evaluates proposals that seem to have a good chance of being implemented at a certain point in time, policymakers later on will only get information about the impact of these policies. Alternatives not evaluated will face a comparative disadvantage in the next round of policy setting as no quantified scientific insights can be brought forward to defend such alternatives. Therefore both such a “realistic” mode of scenario development as well as
the more “explorative” mode assessing option for scaling up climate policy ambition as pursued here should continue to coexist in future literature.

The benefit of representing structurally different policy alternatives can be greater when applied to more disaggregated models. As we have seen the consideration of different indicators leads to the identification of trade-offs among different policy instruments. There is no policy alternative that fares best in all of the indicators simultaneously. The economic indicators here are, however, only proxies to represent different socio-economic challenges. Therefore a modeling framework that captures more of these challenges like, for example, distributional aspects explicitly could lead to deeper insights. A single modeling framework that is both detailed enough to capture all relevant energy system dynamics identified here and at the same time disaggregated enough to explore distribution between different groups in society will be difficult to build. It seems more promising to establish an iterative mode of joint scenario development in two models with specific strengths each.

One of the contributions of this thesis is the identification of various crucial energy system dynamics. Due to the comparative strengths of the employed models, most of these dynamics fall under the supply side of the energy system. Both in the analysis of energy systems and in technology innovation support, a clear dominance of the supply side over the end-use side can be observed (Wilson et al., 2012b). For the analysis part, there are many justifications why this is the case but nevertheless, the underdeveloped understanding of energy demand side dynamics poses a serious threat to the cost-effective achievement of energy targets related to climate change, energy security or economic development. In few sectors and jurisdictions, the acknowledgement of the importance of the demand-side has led to the implementation of policies targeted specifically at more sustainable energy end-use. To include such kind of policies into policy analyses is therefore imperative for the future, because only then a comparative evaluation can weigh opportunities and risks on both the supply and demand side.

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Statement of Contributions

The five core chapters of this thesis (Chapters 2 to 6) were conceptually discussed between the author of this thesis and his principle advisor, Prof. Dr. Ottmar Edenhofer, as well as the direct supervisor, Dr. Gunnar Luderer. They are the result of collaborations with a number of colleagues at PIK and other research institutes, as indicated for each article below. The author of this thesis has made extensive contributions to the contents of all five papers, from conceptual design, to numerical implementation, to writing.

Chapter 2 The core research question was conceived by Gunnar Luderer. The scenario design was developed by GL, Robert Pietzcker, Elmar Kriegler, and Christoph Bertram. Both model improvement and calculation of the actual scenario ensembles were performed by CB and RP. Malte Meinshausen calculated the climate response to the emissions from the REMIND scenarios using a probabilistic climate model. GL did most of the data analysis, with contributions from RP and CB. GL wrote the paper with contributions and revisions from all co-authors.

Chapter 3 Gunnar Luderer developed the conceptual design of the article and wrote large parts of the article, with contributions and revisions from all co-authors. Christoph Bertram produced the REMIND scenarios and performed the data analysis together with GL. Elmar Kriegler specified the design of the moderate policy scenarios, with contributions from GL and CB. Katherine Calvin and Enrica De Cian supplied the scenario results for the GCAM and WITCH models.

Chapter 4 Christoph Bertram conceived the main research questions and wrote the article, with contributions and revisions from all co-authors. Keywan Riahi designed the scenario specifications. CB implemented and produced the scenarios in the REMIND model and carried out the data analysis. Nils Johnson, Morna Isaac and Jiyong Eom contributed the results from the MESSAGE, IMAGE and GCAM model and Gunnar Luderer assisted with the interpretation of results, critically reviewed all aspects of the paper and contributed in extensive discussions.

Chapter 5 Jana Schwanitz and Franziska Piontek conceived the main research questions and JS, FP and Christoph Bertram wrote the article. JS gathered and compiled the data for fuel subsidies and taxes and Gunnar Luderer and CB conceptualized and implemented these into the REMIND model. FP produced the scenario runs and JS, FP and CB analyzed and interpreted the results. GL assisted with the interpretation of results and gave valuable feedback.

Chapter 6 Christoph Bertram and Gunnar Luderer designed the research with input by Robert Pietzcker, Elmar Kriegler and Ottmar Edenhofer. CB performed the modelling and data analysis. CB wrote the paper with contributions and edits by all authors.
Tools and Resources

The main method employed for this dissertation is numerical modeling. The software tools used for the modeling, data processing and visualization, as well as for the preparation of the manuscripts are listed below.

**Modeling** The REMIND modeling framework was implemented in GAMS\(^1\). The CONOPT3\(^2\) solver was used to solve the non-linear optimization. All code projects were managed using the Subversion version control system\(^3\).

**Data Processing** For data pre- and postprocessing work, both MathWorks’ MATLAB\(^4\), version 7.5 (R2007b) and Microsoft Excel 2010\(^5\) was used.

**Typesetting** This document was prepared using the Texmaker editor\(^6\) and \LaTeX\(^2\)\(^7\), particularly the pdffpages package to include Chapters 2 to 6 in their original layouts. Chapters 2, 3, 4 and 6 were written with Microsoft Word 2010\(^8\) and Chapter 5 with \LaTeX\(^2\)\(^7\).

**Literature management** Zotero\(^9\) was used for literature management and references were added to the manuscript via BibTeX\(^10\).

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1[^1]: http://www.gams.com
3[^3]: http://subversion.apache.org/
4[^4]: http://www.mathworks.de/products/matlab/
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