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# $CO_2$ emission mitigation and fossil fuel markets: Dynamic and international aspects of climate policies

Nico Bauer [a,*], Valentina Bosetti [b], Meriem Hamdi-Cherif [c], Alban Kitous [d], David McCollum [e], Aurélie Méjean [c], Shilpa Rao [e], Hal Turton [f], Leonidas Paroussos [g], Shuichi Ashina [h], Katherine Calvin [i], Kenichi Wada [j], Detlef van Vuuren [k,l]

[a] *Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany*
[b] *Fondazione Eni Enrico Mattei (FEEM), Milan, Italy*
[c] *Centre International de Recherche sur l'Environnement et le Développement (CIRED), Paris, France*
[d] *Joint Research Centre (JRC), Institute for Prospective Technological Studies (IPTS), Sevilla, Spain*
[e] *International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria*
[f] *Paul Scherrer Institute (PSI), Villigen, Switzerland*
[g] *National Technical University of Athens, Greece*
[h] *National Institute for Environmental Studies (NIES), Tsukuba, Japan*
[i] *Pacific Northwest National Laboratory (PNNL), College Park, MD, USA*
[j] *Research Institute of Innovative Technology for the Earth (RITE), Kyoto, Japan*
[k] *Netherlands Environmental Assessment Agency (PBL), Bilthoven, The Netherlands*
[l] *Utrecht University, Copernicus Institute, Department of Geosciences, Utrecht, The Netherlands*

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## ABSTRACT

This paper explores a multi-model scenario ensemble to assess the impacts of idealized and non-idealized climate change stabilization policies on fossil fuel markets. Under idealized conditions climate policies significantly reduce coal use in the short- and long-term. Reductions in oil and gas use are much smaller, particularly until 2030, but revenues decrease much more because oil and gas prices are higher than coal prices. A first deviation from optimal transition pathways is delayed action that relaxes global emission targets until 2030 in accordance with the Copenhagen pledges. Fossil fuel markets revert back to the no-policy case: though coal use increases strongest, revenue gains are higher for oil and gas. To balance the carbon budget over the 21st century, the long-term reallocation of fossil fuels is significantly larger—twice and more—than the short-term distortion. This amplifying effect results from coal lock-in and inter-fuel substitution effects to balance the full-century carbon budget. The second deviation from the optimal transition pathway relaxes the global participation assumption. The result here is less clear-cut across models, as we find carbon leakage effects ranging from positive to negative because trade and substitution patterns of coal, oil, and gas differ across models. In summary, distortions of fossil fuel markets resulting from relaxed short-term global emission targets are more important and less uncertain than the issue of carbon leakage from early mover action.

## 1. Introduction

Climate change and fossil fuel markets are interrelated. The use of fossil fuels contributes to the lion's share of greenhouse gases (GHG) emissions, in particular $CO_2$ [1]. Correspondingly, efforts to abate GHG emissions to mitigate climate change will likely affect global fossil fuel markets [2]. The response of fossil fuel markets to mitigation efforts will have an important influence on the costs and acceptability of abatement options [3]. The Intergovernmental Panel on Climate Change (IPCC) highlighted this crucial relationship some years ago [4,5].

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* Corresponding author at: P.O. Box 601203, 14412 Potsdam, Germany. Tel.: +49 331 288 2540.
*E-mail address:* nico.bauer@pik-potsdam.de (N. Bauer).

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**Table 1**
Description of scenarios developed in the two modeling set-ups of the paper.

| Modeling set-up | Scenario description | Acronym in figures |
|---|---|---|
| (1) Global timing of mitigation | Baseline without restrictions on emissions | NoPol |
| | Stabilization with full ‘when’-flexibility | 550-e and 450-e |
| | Stabilization with low global emission target until 2030; 44.2GtCO2/yr in 2030 for fossil fuel and industry only and 46.6GtCO2/yr if land-use change emissions are included | 550-Lo and 450-Lo |
| | Stabilization with high global emission target until 2030 37.3GtCO2/yr in 2030 for fossil fuel and industry only and 39.3GtCO2/yr if land-use change emissions are included | 550-Hi and 450-Hi |
| (2) Fragmented participation | Fragmented policy baseline implementing regional Copenhagen pledges by regional carbon taxes | FragPol |
| | EU implements Road-Map on top of fragmented policy baseline | EU Road-Map |
| | EU and China implement uniform carbon tax from 450 ppm-e case on top of fragmented policy baseline | EU&CHN tax |

Since then research and modeling of fossil fuel markets in state-of-the-art energy and integrated assessment models has improved considerably. Based on these advances, this paper seeks to assess the potential effects on fossil fuel markets induced by climate mitigation policies. A multi-model framework is used to understand these effects.

Policies aimed at long-term climate change stabilization are currently being debated in the political and scientific arena. Research so far focused on cost-optimal scenarios that are implemented by idealized policies—i.e., if no constraints on countries' participation and on the timing of action are imposed so that both ‘when’- and ‘where’-flexibility of emission reductions can be exploited to the largest degree. The international political process, however, has to date failed to negotiate a global, long-term climate change mitigation agreement. Therefore, more recent scenario studies, such as the AMPERE project, analyze deviations from idealized policies. In this context, the present study looks at the implications for fossil fuel markets.

The first deviation from idealized policy scenarios considers global, short-term emission targets derived by current voluntary pledges on the part of individual countries (see Table 1 for a general description). We study the implications of these short-term targets for achieving long-term levels of climate change stabilization, e.g., the 2 °C target. The dilemma we attempt to approximate with this model set-up is on the one hand the Copenhagen Accord that mentions the 2 °C target as a long-term stabilization objective, and on the other hand the short-term pledges actually agreed upon within the Copenhagen Accord (and later re-confirmed in the Cancun Agreement) that appear less ambitious and could make it difficult—if not impossible—to achieve the long-term target. There exist considerable uncertainties regarding the interpretation of some of these pledges (e.g. [6]). Therefore, in this study we include two alternative short-term emission trajectories until 2030 based on two distinct interpretations of the Copenhagen pledges about global near-term emissions: one high trajectory and one low trajectory, which reflect the uncertainty related to the formulation of the pledges. We analyze the implications of these short-term targets on long-term (until 2100) stabilization goals in the form of a stringent 450 ppm $CO_2$-eq and a less stringent 550 ppm $CO_2$-eq stabilization target.

The set-up of our experiment extends the scientific literature looking at the timing of carbon emissions and the resulting mitigation costs [7–12]. However, in contrast to this literature, we develop scenarios that are more in line with real-world policies, and we focus on the inter-temporal re-allocation of fossil fuel use and the resulting impact on fossil fuel revenues. The analysis focuses on the heterogeneity of fossil fuel uses and the inertia of energy sector infrastructure. These key factors determine fossil fuel market outcomes, which are interrelated in a complex way with the intertemporal re-allocation of carbon emissions that are consistent with the carbon budget. Other papers have looked at the fossil fuel markets implications of climate policy. For instance, [13,14] study fossil fuel use in idealized long-term stabilization scenarios, and [14] also tests the sensitivity of fossil fuel availability and changes of fossil fuel rents. Yet, none of these papers looks into short- and long-term implications of deviations from idealized ‘when’-flexibility or the effect of more “realistic” policies.

The second deviation from idealized policies included in our scenario set-up (see Table 1) focuses on the effectiveness of early and unilateral mitigation policies in a fragmented climate policy world and assesses carbon leakage effects (for a broader overview see [15]). As a reference scenario we choose a world with fragmented emission mitigation policies. Because the focus shifts to the regional impacts of polices for this second part, we adopt country-specific Copenhagen pledges as well as specific technology policies. We then consider alterations of this reference case by assuming more stringent climate policies are undertaken in the EU and, in some of the scenarios, in China as well. We analyze the leakage and substitution of coal, oil and gas to explain the large range of carbon leakage.

Carbon leakage is frequently discussed because it has the potential to undermine the environmental effectiveness of unilateral climate policies. [5,16,17][1] argue that the ‘industry channel’[2] and ‘pollution haven’ effects[3] are the main drivers of high carbon leakage effects. [18,19][4] highlight the relatively high importance of the energy market effects that work through re-allocation in fossil energy markets. A series of papers recently published in the *American Economic Review* highlight the scarcity of capital being a fixed factor as a potential reason for negative carbon leakage [20–22]. The

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[1] [17] summarizes the results of the EMF29 model comparison study on carbon leakage.

[2] Production and goods trade are re-allocated so that an emission-constrained countries import goods with high carbon content, which offsets some of the domestic emission reductions. It is also known as competitiveness channel.

[3] Industries relocate from emission-constrained countries to unconstrained countries and therefore part of the emission reduction effort is offset.

[4] [19] relies on a single model framework and, hence, is different in nature to [17].

present study mainly focuses on the energy market effect, but goes beyond previous contributions in four respects. First, it uses a suite of integrated assessment models, thus enabling us to find results robust to a series of assumptions and modeling paradigms. Second, most of the models used here represent the energy sector in a bottom-up way and therefore capture the heterogeneity on a detailed techno-economic level rather than a parameterized macro-economic level. Exceptions are the computable general equilibrium models GEM-E3 and WorldScan2. We highlight that fossil fuel leakage implies inter-fuel substitution in non-abating countries, which dampens carbon leakage and can even turn it negative. The argument is a novelty in the literature and occurs if reduced gas and oil consumption leaks via international markets to non-abating countries, where it then substitutes coal consumption, which in turn reduces $CO_2$ emissions in non-abating countries. Third, all models are dynamic considering gradual changes over time. Finally, the present scenario framework considers strong unilateral emission reduction policies in a few countries in combination with weak policy ambition in other countries. A further unique aspect of the present study is that eleven different models assume harmonized baseline assumptions (population, final energy demand, GDP) and standardized policy assumptions. Together the models cover a broad diversity of modeling approaches and parameterizations, which makes it possible to explore uncertainties without relying on only a single model.

This model diversity is an advantage for the present study because real-world fossil fuel markets are characterized by heterogeneity and inertia. Coal, oil and gas differ in regional availability, carbon intensity, prices, conversion technologies, transportation costs, etc. Coal, oil and gas can substitute each other only in certain applications. Moreover, some applications of coal and gas are amenable to carbon capture and sequestration (CCS) to supply low-carbon energy. Finally, fossil fuel related infrastructure is inert. For all of these reasons, the models' representations of fossil fuel markets are very different and, thus, the resulting scenarios often strongly differ. Utilization of a multi-model ensemble helps to understand the key differences and, by extension, to assess the uncertainties of climate change mitigation policies.

The remainder of the paper is structured as follows. Section 2 gives an overview of general model features. Section 3 presents results for emissions and fossil fuel use for a no-policy baseline and two stabilization targets under idealized policy assumptions. Section 4 studies the deviations from the assumption of full 'when'-flexibility, and Section 5 addresses the leakage issue in a fragmented policy regime. Section 6 summarizes and discusses the key findings of this study. This paper comes with Supporting Online Material.

## 2. Methods

The models participating in this study are all known in the scientific literature, as they have previously been used in the assessment of climate change mitigation policies. All are global, long-term models and comprise a detailed energy sector representation including fossil fuel trade. In addition, all differentiate coal, oil and gas markets and include the option of carbon capture and sequestration. The main differences relevant for the present study (summarized in Table 2) relate to the models' solution structures, with recursive dynamic (RD) models solving a sequence of equilibria and fully inter-temporal (IT) models having perfect foresight. Furthermore, most models assume optimal emission timing either by the IT feature or because a Hotelling-type carbon price path is implemented to comply with a carbon budget. Early retirement of existing infrastructure (like coal power plants) is also a feature included in a sub-set of models. Some models not only account for $CO_2$ emissions from fossil fuel and industry (FFI), but also consider land-use change (LUC) carbon emissions from the land-use sector. Finally, models differ in their fossil fuel price-formation mechanisms (see Table S1 for details). It should be noted, however, that not all models participated in all parts of the study.

## 3. Climate change stabilization with full 'when'- and 'where'-flexibility

In this section we present the results for three scenarios that (i) consider full availability of the technology portfolio and (ii) assume harmonized development of final energy demand[5] across models. The *NoPol* case assumes no policies for limiting future GHG emissions. It serves as a counterfactual reference scenario to evaluate the use of fossil fuels and the subsequent mitigation effort needed to achieve climate change stabilization. We focus on two stabilization scenarios here: the *550-e* and *450-e*, which implement carbon budgets[6] constraining cumulative emissions until 2100 that are consistent with GHG concentrations of 550 ppm $CO_2$-eq and 450 ppm $CO_2$-eq, respectively, at the end of the century. The stabilization scenarios allow full 'when' and 'where' flexibility for carbon emission paths.[7] If models consider $CO_2$ emissions from the land-use sector, then inter-sectoral mitigation flexibility is allowed.

Fig. 1 shows two key results for the cumulative $CO_2$ emissions. First, in the no-policy case (NoPol) near-term (2011–2030) emissions are below 1000 $GtCO_2$ whereas long-term (2031–2100) emissions reach no less than 5500 $GtCO_2$ and can even exceed 8000 $GtCO_2$. Second, near-term reductions are comparatively less than long-term reductions to achieve the stabilization targets. Near-term reduction is 5–35% from baseline in the 550-e case while it is up to 18%-points larger in the 450-e case. The long-term reduction is 70–85% from baseline in the 550-e case and 10–20%-points more in the 450-e case. In the longer term the land-use sector of some models (MESSAGE, DNE21) realize negative emissions as this

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[5] The global improvement rate of final energy intensity is assumed at ~1.3%/yr. This leads to a range of 655–725 EJ/yr in 2050 and 910–1000 EJ/yr in 2100.

[6] The carbon budgets 2000–2100 are differentiated depending on the specific model (i) runs until 2050 or 2100 and (ii) includes the land use sector emissions. For long-term models the carbon budget is 1500 $GtCO_2$ with and 1400 $GtCO_2$ without emissions from the land-use sector. For models only focusing on the time horizon up to 2050 the budget is 1300 $GtCO_2$.

[7] For models applying intertemporal optimization for deriving the carbon emission path 'when' flexibility is related to the optimal timing of emission mitigation. Some recursive dynamic models (GCAM) assume exponentially increasing carbon taxes that reconcile the optimality conditions of the Hotelling model. Other recursive dynamic models (IMACLIM, IMAGE) do not assume exponentially increasing carbon taxes. In IMAGE the carbon tax path is determined by a cost minimization based on a large number of runs. There is, however, no algorithm applied to determine this price path but is determined by the model teams. The IMACLIM model adjusts the carbon emission path. The overview paper by Kriegler et al. [15] discusses this issue in more detail.

**Table 2**
Overview of models participating in this study regarding emission timing and fragmented regimes.

| | DNE21+ | GCAM | GEM-E3 | IMACLIM | IMAGE | MERGE-ETL | MESSAGE | POLES | REMIND | WITCH | WorldScan2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time horizon | 2050 | 2100 | 2050 | 2100 | 2100 | 2100 | 2100 | 2100 | 2100 | 2100 | 2050 |
| Land-use sector $CO_2$ emissions | ♪ | ♪ | | | | ♪ | ♪ | | ♪ | ♪ | |
| ‘when’-flexibility participation | ♪ | ♪ | | ♪ | ♪ | ♪ | ♪ | ♪ | ♪ | ♪ | |
| Dynamic structure[a] | IT | RD | RD | RD | RD | IT | IT | RD | IT | IT | RD |
| Optimal emission timing | ♪ | ♪ | | | ♪ | ♪ | ♪ | | ♪ | ♪ | |
| Early retirement | ♪ | ♪ | | ♪ | | | ♪ | ♪ | ♪ | ♪ | ♪ |
| *Fragmented policies participation* | | | | | | | | | | | |
| Scenario: EU acts | ♪ | ♪ | ♪ | ♪ | ♪ | ♪ | ♪ | ♪ | ♪ | ♪ | ♪ |
| Scenario: China and EU act | | ♪ | ♪ | ♪ | ♪ | ♪ | | ♪ | ♪ | ♪ | |

[a] IT means inter-temporal, RD means recursive dynamic.

sector also reacts to the carbon price signal. IMAGE instead increases the CO2 emissions due to deforestation for increased bioenergy supply.

Fig. 2 shows the cumulative use of fossil fuels across the different models over varying time frames, where the dark color shadings indicate short-term consumption (2011–2030) and light color shadings depict long-term consumption (2030–2011). The hatched bars indicate the combination with CCS. In the absence of emissions limits (NoPol), the short-term cumulative use of oil until 2030 is around 4.1ZJ (−0.3; +0.9). Also for natural gas the short-term baselines roughly agree around 2.8 ZJ (−0.4; +0.7). The short-term differences in cumulative coal use are more uncertain, however, with a range of 3.3 to 6 ZJ around a median of 3.9ZJ.

The NoPol baseline scenarios generally disagree regarding the structure of fossil fuel use in the longer term (indicated by the light color shading). The highest long-term cumulative use of oil is computed by the WITCH and MESSAGE models, whereas the REMIND baseline scenario shows the highest gas use. Two models (IMACLIM and MERGE-ETL) make more conservative assumptions about oil and gas availability; hence, the most economical alternative in these cases is the large scale use of relatively cheap coal. In both models, this in turn increases total fossil fuel use and boosts $CO_2$ emissions because final energy demand is supplied by a relatively inefficient and carbon-intensive energy sector. This explains the relatively high $CO_2$ emissions of both models previously shown in Fig. 1. These results indicate that in the long run limited availability of oil and gas is substituted by higher coal use, implying higher $CO_2$ emissions if no carbon emission limitations are imposed.

Imposing climate change stabilization targets leads to competition between coal, oil and gas use for the disposal space of carbon in the atmosphere (these cases are also

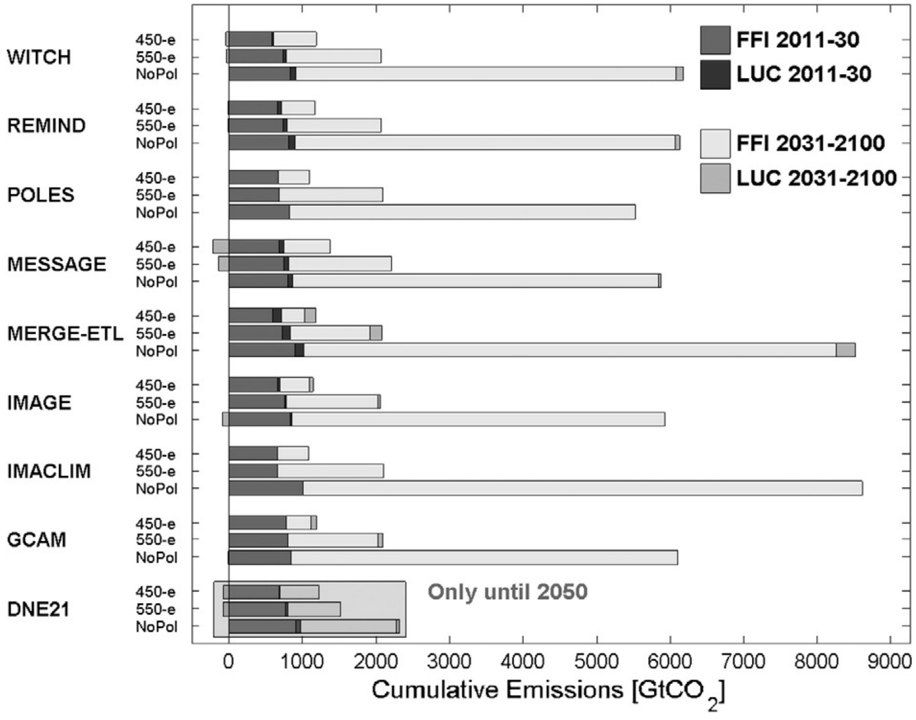

**Fig. 1.** Cumulative global $CO_2$ emissions and fossil fuel use differentiated between short and long term. FFI means $CO_2$ emissions from fossil fuel and industry and LUC indicates those from land-use change.

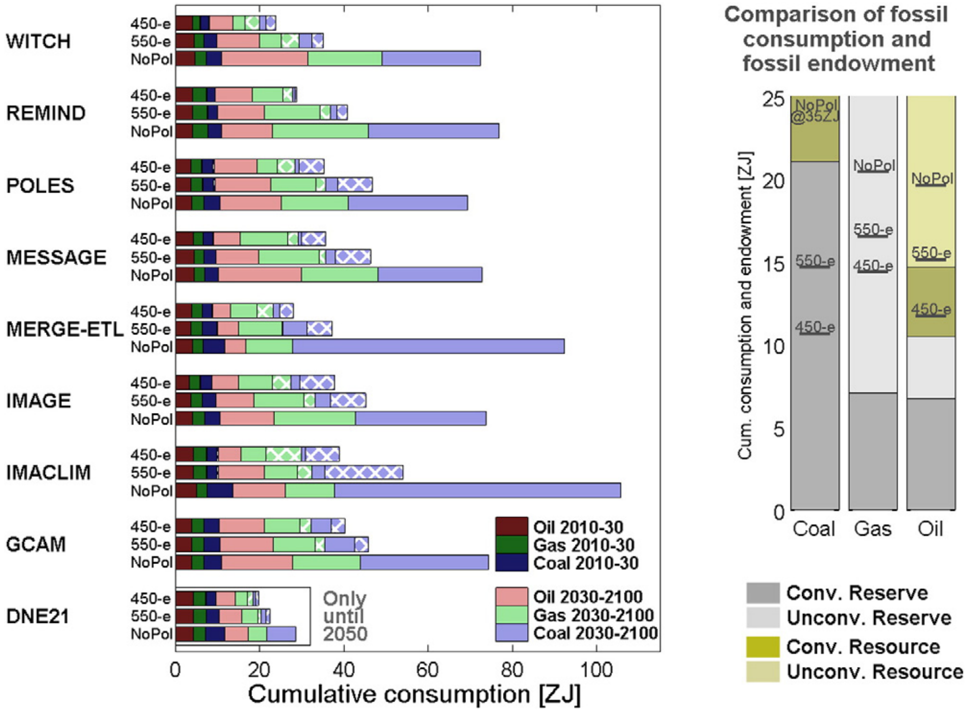

**Fig. 2.** Cumulative global fossil fuel use in the no policy reference case and two stabilization scenarios with full 'when' and 'where'-flexibility. Hatched bars indicate fossil fuel use in combination with CCS. The bars on the right compare the medians of cumulative global fossil fuel use 2011–2100 in the scenarios with assessments of fossil fuel availability. Data taken from [23]. Note: the order of extraction in the models does not necessarily coincide with the stack order of the bars.

depicted in Fig. 2 for the sake of comparison). Such targets lead to drastic reductions in the demand for coal, oil and gas over the entire 21st century, though the short-run picture is quite diverse. Compared to the baseline, cumulative coal use until 2030 is reduced by 24%, ranging between 10 and 55% for the 550-e target; this reduction is more significant for the 450-e target with a median of 41% (13–56%). Oil use drops by only 4% (0–15%) for the 550-e target and is still as small as 6% (0–17%) for the 450-e case. The changes in gas use are ambiguous: it can decrease by 11% or increase up to 26% in the 550-e case, with an even higher uncertainty (−28% to +27%) in the stricter 450-e case, whereas the median shows only a slight reduction for both targets. The combination of fossil fuels with CCS is relatively small until 2030. Gas with CCS reaches a cumulative maximum of 130 EJ (DNE21+ in 450-e) and coal with CCS is never higher than 400 EJ (POLES in 550-e).

Long-term fossil fuel use is drastically reduced by climate stabilization policies. The median of total fossil fuel use is 45 ZJ in the 550-e case and still 35 ZJ in the 450-e case. The lowest levels are reported by the WITCH model (35 ZJ for 550-e and 24 ZJ for 450-e). Models that rely more on CCS show higher fossil fuel use. Most coal is used in combination with CCS, and the use of this technology option is generally higher in the 550-e than in the 450-e case because of the relatively high residual emissions that are not captured. Gas with CCS is also used to a considerable degree. In contrast to coal, this technology is used at a larger scale in the 450-e than in the 550-e case. Interesting to note: some models (MERGE-ETL, IMAGE, IMACLIM) achieve the 450-e target with higher cumulative coal than oil use, whereas other models strongly reduce coal after 2030 (e.g. REMIND).

Finally, we compare the ensemble median cumulative fossil fuel consumption over the 21st century with fossil fuel endowments (right part of Fig. 2). The use of fossil fuels in baseline scenarios exceeds overall conventional reserves. While gas use does not exhaust the total reserve, coal reserves are not sufficient to supply the growing demand. Oil use would even be higher than the entire reserves and conventional resources. In stabilization scenarios much of the coal reserve would be left underground, but oil and gas consumption is still higher than the conventional reserves. Oil use in the 450-e case would even be nearly as high as the known reserves of oil.

## 4. Long-term climate change stabilization with restricted 'when'-flexibility

In this section we analyze the effect of combining the two long-term stabilization targets with two short-term emission constraints. Prescribing short-term emission pathways until 2030 constrains the 'when'-flexibility, since the long-term emission budget has to be met. We apply a high and a low short-term emission constraint denoted HST and LST, respectively. The HST requires 2030 carbon emissions to stay below 44.2 GtCO2/yr if only fossil fuel and industry emissions are considered, and below 46.6 GtCO2/yr if also land-use emissions are represented in the model. For the LST cases the corresponding values are 37.3 and 39.3 GtCO2/yr, respectively. These emission targets are below the baseline emission pathways of all models but typically exceed the 2030 levels of the optimal transition pathways, 550-e and 450-e (see Fig. 1)—though for some models they are lower. In the following discussion we generally refer to the case where short-term targets lead to emissions in 2030 that are higher than the optimal transition pathways; otherwise it is indicated explicitly. The imposition of short-term emission targets could in certain instances render it impossible to achieve the stabilization targets. These scenarios are interpreted to be non-solvable and are highlighted in the following graphs; they are not part of the analysis, however. [24,25] derive the short-term emission targets and provide a detailed analysis of time paths of individual models; we will only focus on cumulative short- and long-term emissions.

Figure S1 of the supporting online material shows the dynamic re-allocation of $CO_2$ emissions across models and scenarios. The total dynamic re-allocation of carbon emissions in the 550-e case can exceed 100 $GtCO_2$, but is less than 5% of the total emission budget for the full century. In the 450-e case the figure is as high as 230 $GtCO_2$, which amounts to 15% of the more stringent budget. If short-term targets lead to excess emissions, scenarios that also represent land-use emissions show that these additional land-use emissions (short and long-term) trade off with long-term emissions from fossil-fuel and industry. Hence, short-term limitations on 'when'-flexibility have an inter-sectoral effect that requires stronger emission reductions from fossil fuels and industry to comply with a long-term carbon budget.

### *4.1. Constrained 'when'-flexibility and fossil fuel use*

In this sub-section we analyze the implication of the dynamic re-allocation of the carbon emission budget on the allocation of fossil fuels. We calculate the differences between the stabilization cases with full 'when'-flexibility and the case with short-term emission targets. We do this separately for the short- and the long-term period to measure the dynamic reallocation. We also differentiate between coal, oil and gas as well as with and without CCS. Therefore we also capture the inter-fuel dimension of the reallocation.

Fig. 3 shows the dynamic re-allocation of global coal, oil and gas use. A robust finding is that under short-term emission targets the strongest short-term increase is found for coal. This result is not a surprise: if near term emission targets are relaxed towards the no-policy baseline emissions, the reversal of absolute coal use back to the baseline is stronger than the reversal of oil or gas. Only the models WITCH and POLES show significant short-term reversal of oil and gas use whereas REMIND, DNE21+, and MERGE-ETL do not show this effect. The latter set of models mostly reduces near-term coal use to achieve the stabilization targets (see Fig. 2). With relaxed emission targets Fig. 3 also shows that coal and gas use with CCS is reduced, but the effect is relatively small because its short-term diffusion is rather limited.

The short-term emission cap induces a distortion from the solution that makes full use of 'when'-flexibility. A robust result for all models[8] and scenarios is that the longer-term reallocation of fossil energy to balance the carbon budget is larger than the short term distortion. This can be observed from the fact that the sum of long-term components (light colors) is larger than the short-term components (dark colors). Four main effects help to explain the long/short-term amplification shown in Fig. 3. These effects are at work to different degrees in the various scenarios and models.

1. Carbon-intensity and CCS effect: We noted above that the higher short-term use of coal is the largest effect. This is balanced by long-term reductions of oil and gas. Since oil and gas have lower carbon intensities, the corresponding reduction in energy units must be larger. This can be observed, for example, in the WITCH model. In a considerable number of scenarios, the dynamic carbon emission compensation is achieved by a reduction of oil consumption. The carbon intensity effect leads to lower total oil consumption over the 21st century in 17 out of 26 relevant scenarios. The CCS effect is a specific variant of the carbon intensity effect. The residual emissions of CCS plants are still using up the carbon budget because the carbon capture rate is below 100%. If compliance with the carbon budget requires reducing long-run use of CCS, the fossil fuel reduction in energy units needs be much larger than the higher use fossil fuels without CCS to balance the carbon budget. The higher the capture rate of the originally applied technologies (e.g. in power plants), the higher must be the total reduction for long-term emission compensation because only the residual emissions are accounted to balance the emission budget. The effect can lead to a total reduction in the use of coal (POLES, MESSAGE) or gas (REMIND). Also some models (REMIND, WITCH, DNE21+) are constrained by the CCS capacity and as bio-energy with CCS increases to meet the carbon budget, the use of fossil fuels with CCS decreases (see Figure S2).
2. Coal lock-in effect: Higher near-term use of coal also tends to continue after 2030 and implies higher cumulative long-term coal use (positive light blue component). This is due to a lock-in of coal-fuelled infrastructure that keeps on operating because early retirement is not assumed or constrained.[9] Generally this effect is even larger for the stricter stabilization target, because the forgone emission reduction due to the short-term emission target is even larger in the 450-e case. This effect is at work in nearly all models and scenarios. This crucial feature is different in the WITCH model that assumes full flexibility of early retirement and, thus, can put more quickly a break on coal use to avoid the lock-in, which is indicated by the light blue bar being placed on the left part of Fig. 3.
3. Inter-fuel substitution effect: The long-term use of coal is strongly reduced and partially substituted by higher use of oil and/or gas. For instance, POLES solves the short-term distortion in the two 550-e cases by inducing inter-fuel substitution in the long-term.
4. Intersectoral re-allocation effect: As noted above, $CO_2$ emissions from fossil fuels and industry trade-off with land-use emissions. Higher near-term land-use emissions

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[8] The model DNE21+ does not meet the requirement to reallocate the budget between short- and long-term at equal shares. See Fig. 3. Therefore, the amplification ratio can fall below 1.

[9] [22] show the exact extent of early retirement of coal capacities in all models and different scenarios.

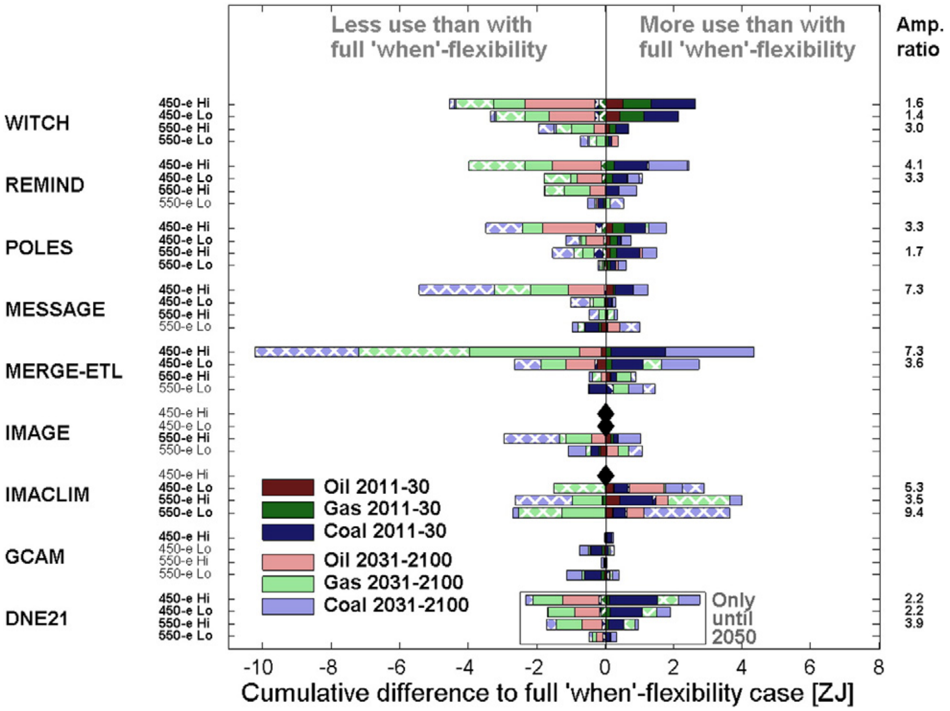

**Fig. 3.** Changes of global fossil fuel use of cases with constrained 'when'-flexibility compared with respect to the first best solution shown in Fig. 2. Hatched bars indicate fossil fuel use in combination with CCS. Non-solvable scenarios are marked by black diamonds. In case the short-term emission target is higher than the emissions with full 'when'-flexibility the scenario is indicated by bold fond (taken from Figure S1). Note that positive and negative components of each scenario do not necessarily add up to zero. The amplification ratio is given on the right side of the plot. It is defined as the sum of absolute values of long-term components put into relation with the sum of the positive short-term components.

are compensated by lower fossil fuel and industry emissions in the longer-term.

The strength of the amplification effect can be measured by the amplification ratio. The sum of absolute values of long-term components is put into relation with the sum of the positive short-term components. The values are reported on the far right of Fig. 3, if the short-term distortion exceeds 500 EJ. The carbon intensity effect seems relatively small. WITCH mainly relies on the long-term reduction of oil and gas to compensate for higher near-term coal use implying a relatively small amplification ratio. The carbon lock-in effect amplifies the initial distortion more effectively. REMIND and MERGE-ETL show amplification ratios above two. The various amplification effects are, however, not independent. For instance, the coal lock-in effect amplifies the carbon intensity and the CCS effect, but the carbon intensity effect dampens the inter-fuel substitution effect.

The various models deal differently with the dynamic trade-off to comply with the long-term carbon budgets. Some models show characteristic reallocation patterns across scenarios; they mainly differ regarding the scales of the various components. Such a model-specific reallocation pattern is shown for the WITCH scenarios, where the initially higher use of coal is reduced by stronger reductions of oil and gas. In REMIND also the significant coal lock-in effect needs to be balance, which is partially achieved by less use of gas with CCS. AIM-Enduse also reduces the long-term use of coal without CCS. POLES relies on long-term inter-fuel substitution in the 550-e cases. In the two 450-e cases, however, the reaction is similar to REMIND. Here, the influence of the long-term stabilization target dominates the differences between the short-term emission targets. Also in MERGE-ETL the two 450-e cases show a robust pattern (similar to REMIND), whereas the 550-e HST case shows some inter-fuel substitution effect. IMACLIM scenarios show different patterns making use of various reallocation options. The re-allocation of fossil fuels regarding CCS fueled plants leads to high amplification ratios.

### 4.2. Fossil fuel revenue effects

The change in the net present value of fossil fuel revenues is used to assess the economic impact of climate change stabilization with and without 'when'-flexibility. Revenues are computed by weighting fossil fuel consumption per period with the then current prices[10] to be paid by demand sectors. Alternatively, profits or rents could be used as an indicator to assess the wealth of fossil fuel owners [14]. Revenues also include the costs of extracting and transporting the fossil fuels (i.e. the factor incomes for labor, equipment, services, etc.), and therefore reflect the situation of the entire sector. Additionally, some models consider resource taxes and royalties. Fossil fuel prices vary significantly across models (see Figure S3) but are within the range of historical fossil fuel prices, which differed significantly over last two decades [26]. This range is due to different modeling approaches for the price formation

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[10] This means the US$ prices deflated to the year 2005.

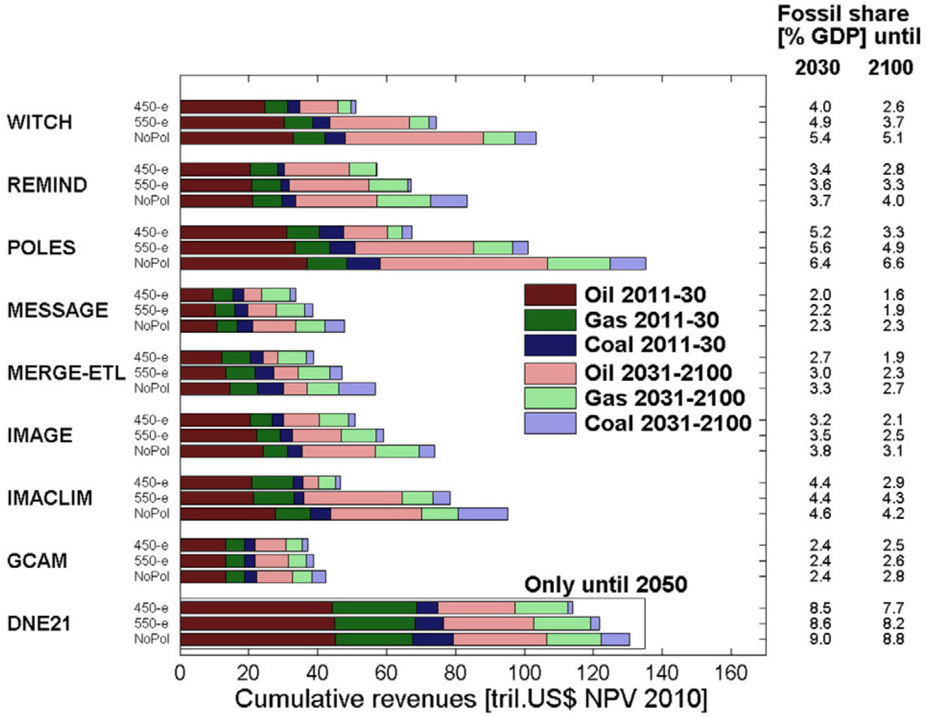

**Fig. 4.** Net present value of cumulative revenues 2011–2100 of fossil fuels in scenarios with full when flexibility. The net present value is for the year 2011 applying a discount rate of 5% per year. The numbers on the right to the graph represent the fossil fuel share of GDP 2011–30 and 2031–2100, also based on net present values.

mechanism. Table S1 gives an overview on the differences. One feature is shared by all models: carbon prices *affect* the market prices of fossil fuels, but the emission penalty from emitting $CO_2$ after combustion is *excluded*. The emission penalty is paid by down-stream sectors depending on their emissions.

Fig. 4 shows fossil fuel revenues for the no-policy baseline and the two stabilization scenarios with full 'when'-flexibility. The model uncertainty exceeds the uncertainty of climate policies because fossil fuel prices vary significantly across models. Oil revenues account for most of the diversity because oil prices are higher than gas and coal prices and oil prices vary most across models. Revenue in the no-policy baseline ranges from 42 tril.US$ for GCAM to 135 tril.US$ for POLES. Most models with high revenues in the baseline also show large reductions in the stabilization cases.[11] For instance, for the POLES model the total revenue in the 450-e case is halved to 67 tril.US$, whereas it is only slightly reduced (by 12%) to 37 tril.US$ in the GCAM model. Although the uncertainty across models is considerable, a number of robust patterns regarding the fossil fuel share of GDP emerge; shown on the right of the plot. Firstly, fossil fuel shares decrease over time. This means that the growth rate of GDP outpaces the growth rate of fossil fuel revenues.[12] Second, shares decrease with the stringency of the climate change mitigation.

Next, we analyze the change in fossil fuel revenues due to constraints on 'when'-flexibility. For the analysis we take the long-term stabilization target as given and examine the short- and long-term revenue effects of choosing the high or low short-term emission target. Fig. 5 shows the results for the differences in revenues in a similar way like in Fig. 3.

Short-term fossil revenues increase if near-term carbon emissions are higher because fossil fuel markets revert back to the baseline scenario: generally, more fossil fuels are sold at higher prices and, hence, revenues increase. Coal revenues increase only slightly, though the quantity effect in energy units is the most significant (as can be seen in Fig. 3). The models with high fossil revenues in the baseline (WITCH, POLES, IMACLIM) also have the highest short-term revenue gains, mainly from oil and gas. These models have high baseline oil prices. With full 'when'-flexibility, these prices would decrease significantly. With higher near-term emission targets, they revert back to the baseline. In REMIND the coal component is largest in the short-term; the oil revenue increases also due to slight price increases. For MERGE-ETL the coal and oil revenue components are roughly equal, but oil consumption is even less with reduced 'when'-flexibility, and the oil price effect dominates. Hence, for most models in the short-run oil and gas revenues increase more from relaxed short-term emission targets than coal revenues, though quantity effects lead to strong relative decrease of coal revenues.

The short-term gains have to be compared with the longer-term effects that are also shown in Fig. 5. The WITCH model indicates that short-term revenue gains over-compensate long-term losses in all scenarios and for each fossil fuel. The

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[11] The model DNE21+ is an exception, because it calibrates paremeters to match the relatively high prices currently observed in the market. The initial calibration of prices means that the reasons behind the prices are not represented explicitly and therefore climate policies do not have a strong effect on these prices.

[12] Exceptions are POLES and REMIND, which show slightly increasing fossil shares in the NoPol scenario.

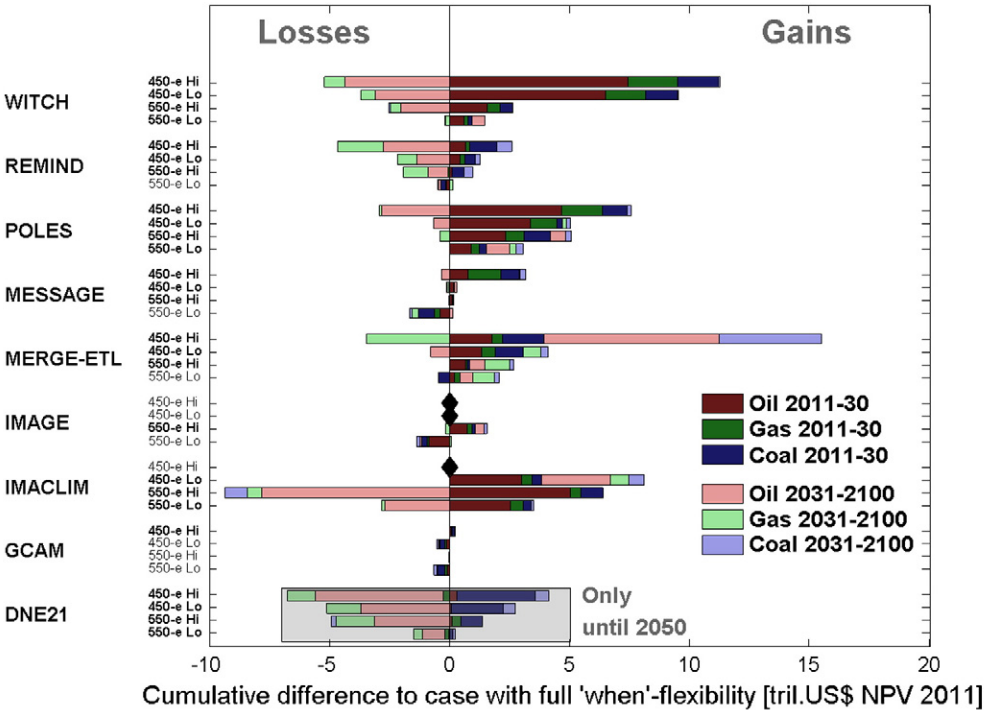

**Fig. 5.** Differences of net present value of cumulative fossil fuel revenues compared with corresponding first best case assuming the same stabilization target. The net present value is for the year 2011 applying a 5% discount rate per year. Non-solvable scenarios are marked by black diamonds.

REMIND model shows a different result: long-term revenue losses exceed short-term gains, especially for oil and gas. In this model the coal lock-in effect requires strong long-term reductions of oil and gas use. For the 550-e cases, the losses also exceed the gains in the POLES model, though the carbon budget is balanced by inter-fuel substitution towards oil and gas. Here, lower prices reduce the revenues more than the higher use increases them. In IMACLIM the comparison varies across cases. MERGE-ETL shows an extreme reaction, since both oil and coal increase in the 450-HST case. This is partly due to high penalties on mining emissions. Additionally, coal revenues are higher due to the coal lock-in effect and oil prices increase due to relative scarcity effects.

A final note: Net present values are sensitive to discount rates. The 5%/yr applied here is a low value compared to the common practice used for investment decisions in the fossil industry, but here we study the entire sector which justifies a low discount rate. A higher discount rate—in the first place—decreases the net present values of fossil fuel revenues. The second order effect would imply a smaller relative weight on longer-term revenue changes and therefore the results would indicate a stronger preference for relaxed short-term emission targets.

## 5. Carbon leakage in a world with fragmented emission policies

The international aspects of fragmented climate change mitigation policies are assessed by comparing the reference policy case with two scenarios in which the EU and China strengthen their policy ambition by increasing emission mitigation. Carbon leakage through international fossil fuel market re-allocation is one of the key risks of additional uni-lateral and early action because it may undermine its environmental effectiveness.

The reference policy case assumes a weak and fragmented policy regime. The implementation of the reference policy case is harmonized across models regarding proposed policies to expand capacities of low-carbon technologies until 2020 as well as carbon emission targets in 2020 based on regional Copenhagen pledges and continued improvements of GHG intensities of GDP[13] thereafter. Given this setting each model derives regional carbon prices that are consistent with the emission targets. To assess the carbon leakage effect, the modeling teams applied carbon prices instead of the quantity targets[14] for the two scenarios with additional policy ambitions.

These scenarios assume specific measures by the EU and China to achieve additional emission reductions:

1. *EU-Road Map*: The EU adopts the climate policy Road-Map until 2030, whereas other regions adopt the pledges. The EU-Road-Map requires stronger emission reductions than

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[13] In this section we use the scenarios computed within work-package 3 of the AMPERE project. Here, the GDP assumptions were harmonized to meet similar economic development levels. Hence, GHG intensity improvements lead to similar—though not equal—emission limitation trajectories.

[14] In case of strict quantity targets the effects of carbon leakage would be simply excluded because it would not allow the possibility that $CO_2$ emissions go above the levels of the reference policy case.

the EU pledges. The implementation is harmonized across models to achieve $CO_2$ emission reduction targets. Some models also applied the target to reduce the final energy intensity of GDP by 20% until 2020.

2. *EU and China carbon tax*: The EU and China nationally apply a uniform carbon tax with domestic revenue recycling. The tax rates differ between models, but they are consistently derived with each model by imposing a long-term $CO_2$ emission budget that is consistent with a 450 ppm-$CO_2$ equivalent target.

We look specifically at leakage effects until 2030. A longer duration of unilateral policies is not reasonable because other regions would either join the mitigation policies or early movers would drop their policies. We focus on (i) the international fossil fuel leakage and (ii) inter-fuel substitution in markets of early movers and other regions.

*Table 3 summarizes the carbon leakage effects for the two scenarios and for each model. The* cumulative emission reduction through 2030 in the EU by applying the road map is as high as 11.3 $GtCO_2$. The emissions in the Rest-of-World may increase by up to 2.3 GtCO2, but may also decrease slightly, depending on the model. The resulting leakage rates span a broad range and three out of eleven models compute negative carbon leakage rates. This happens if reduced gas and oil use in abating countries leaks via international markets to non-abating countries, where it substitutes coal consumption (see below for details). It must be noted that in all models, including the inter-temporal models, the rest of the world does not expect future carbon pricing in the pre-2030 phase and therefore there is no readjustment of their emissions path. This simplification implies that the carbon leakage is at the upper end.

The situation is different if the EU and China implement the carbon tax. First, the combined emission reduction is much larger compared to the case in which the EU acts alone. And secondly, no model shows a notable leakage rate (<-1%).

There is no clear pattern how the leakage rates from one model change between the two cases. One model (MERGE-ETL) shows a high positive leakage rate in both cases, whereas POLES shows always a small positive leakage. REMIND changes from a slightly negative to a medium positive leakage rate if China also acts. For WITCH, POLES and GEM-E3, the carbon leakage rate decreases if China also strengthens its mitigation ambition; and in case of GCAM the leakage rate even becomes negative. The following fossil fuel market analysis helps to reconcile this diversity.

Fig. 6 shows the reallocation of fossil fuels for the case that EU alone implements the road map on top of the weak policies. Some qualitative results are robust across models. First, the EU generally uses less coal, oil and gas without CCS, but some coal and gas is used in combination with CCS. The reduction of oil use in the EU is subject to high leakage in five models (WITCH, POLES, MESSAGE, MERGE-ETL and GEM-E3). Significant positive coal leakage is found in three cases (WorldScan2, MERGE-ETL and IMACLIM), whereas the intra-European reallocation of coal towards CCS use is found in five models. Also, some fossil fuels leak into CCS plants outside the EU, if the carbon prices in other regions are sufficiently high (IMACLIM).

In addition to the general results, it is useful to take a detailed look into some models to explain the range of leakage rates. The carbon leakage in WITCH is mainly generated by an oil leakage rate of 53%. REMIND assumes high gas use in the baseline in the EU, which leads to a relatively strong reduction compared with coal. This reduced gas consumption is subject to a leakage rate of nearly 50%. The higher gas supply helps to substitute coal in the rest of the world and therefore the reduction of coal use outside the EU is even higher than in the EU itself. Qualitatively the same effect is found in POLES, but here the fossil fuel substitution effect outside the EU is not large enough to result in negative carbon leakage. In MESSAGE, the EU reduces oil and gas use significantly, and that partially leaks to other countries. This again leads to a substitution effect with coal, which implies negative carbon leakage. However, the intra-EU reallocation of gas towards applications with CCS is even larger than the international gas leakage effect. MERGE-ETL assumes high coal use in the baseline in the EU due to globally scarce hydro-carbon availability. Therefore, the EU mainly reduces the use of coal and that is subject to a leakage rate of 50%. The oil leakage rate in MERGE-ETL even exceeds 100%. The inter-fuel substitution caused by increasing gas consumption in the EU can lead to a reverse leakage in the

**Table 3**

Changes in cumulative emissions 2011—2030 in acting regions and the rest of the world compared with reference policy case. The leakage rate is the ratio of changes in emissions in rest of the world relative to the changes in emissions in the acting regions. A negative leakage rate implies that the emissions in the rest of the world decrease if the acting regions decrease their own emissions.

| | DNE21+ | GCAM | GEM-E3 | IMACLIM | IMAGE | MERGE-ETL | MESSAGE | POLES | REMIND | WITCH | WorldScan2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EU27 applies Road-Map | | | | | | | | | | | |
| Emission reduction in EU27 [$GtCO_2$] | 1.8 | 7.0 | 3.4 | 4.5 | 4.6 | 5.0 | 3.7 | 4.6 | 3.1 | 11.3 | 2.6 |
| Emission increase in Rest-of-World [$GtCO_2$] | 0.1 | 0.3 | 0.7 | 0.3 | −0.2 | 2.3 | −0.1 | 0.4 | 0.1 | 1.3 | 0.5 |
| Leakage Rate [%] | 5.7 | 4.4 | 21.6 | 6.1 | −3.6 | 46.5 | −3.2 | 7.8 | −1.1 | 11.9 | 20.5 |
| EU27&China apply carbon tax | | | | | | | | | | | |
| Emission reduction in EU27&China [$GtCO_2$] | | 17.9 | 89.1 | 38.2 | 49.8 | 76.6 | | 85.8 | 57.0 | 86.2 | |
| Emission increase in Rest-of-World [$GtCO_2$] | | −0.1 | 2.1 | 3.1 | −0.3 | 47.8 | | 1.1 | 4.8 | 6.2 | |
| Leakage Rate [%] | | −0.8 | 2.4 | 8.2 | −0.6 | 62.3 | | 1.3 | 8.4 | 7.1 | |

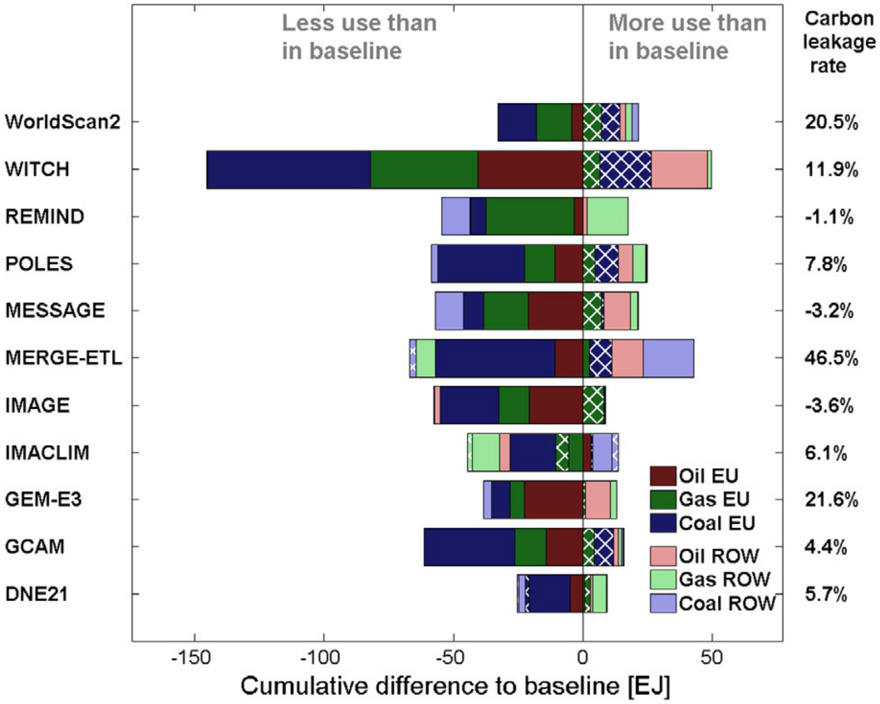

**Fig. 6.** Changes of cumulative use of fossil energy carriers 2010–30 in EU27 and Rest of World compared with baseline, when EU27 applies the Road Map. Hatched bars indicate fossil fuel use in combination with CCS. Bars without hatches indicate fossil fuel use without CCS.

rest of the world. GEM-E3 also shows reduced coal use outside the EU, but here the effect is not strong enough to imply a negative carbon leakage rate, as it does in REMIND and MESSAGE. The 22% carbon leakage rate computed with GEM-E3 is made up of different sectoral leakage rates. The highest sectoral leakage rates in 2030 occur for the energy conversion sector (31%) and energy intensive industries (19%). The service sector experiences a negative carbon leakage rate of −17% [27]. Finally, the models POLES, IMAGE, IMACLIM, GCAM, and DNE-21 generally show small international fossil fuel leakage.

The situation is different if we look at the scenario in which the EU and China apply the “uniform 450 ppm-e carbon tax”. Fig. 7 shows the effects on the fossil fuel markets for eight models in the same format as the previous figure. The most robust finding across models is that China and the EU reduce coal consumption. This is mainly due to commonly assumed high coal baselines in China. However, only two models show notable leakage of coal (REMIND, MERGE-ETL), but four models show the switch towards coal with CCS (WITCH, POLES, IMACLIM, GEM-E3). As in the previous case, the international coal market is relatively unresponsive even with the large coal reduction in China (see Figure S4 for price effects). The change in oil use is ambiguous. EU and China increase oil consumption in two models (REMIND, GCAM), though the magnitude is rather small. Only three models show the oil leakage effect at a notable scale (WITCH, MERGE-ETL, GEM-E3). The reallocation of gas use is even more ambiguous. Only three models (POLES, GEM-E3, IMACLIM) show the expected leakage for natural gas, but four models show increasing gas consumption in the acting regions and two models show reversed gas leakage (REMIND, MERGE-ETL).

Again, we take a closer look into the diversity of model results. MERGE-ETL and REMIND show normal coal and reversed gas leakage. MERGE-ETL also shows considerable oil leakage. Oil leakage is the only considerable effect in WITCH, though coal and gas are also reduced. Again, the models POLES, IMAGE, GCAM, and IMACLIM show negligible fossil fuel leakage, though total fossil fuel reduction is now larger than in the case of EU acting alone. The reduction of the carbon leakage rates reported in Table 3 is due to the relatively stronger reduction of coal, which is less responsive to leakage than oil and gas.

Comparing the two policy cases, models agree that reductions of coal use are subject to relatively small leakage effects. Coal (as well as gas) may also be reallocated domestically towards plants equipped with CCS and, thus, this share does not leak to international markets. International oil markets are more responsive than coal. International gas markets are also responsive, but it is ambiguous whether gas consumption is increased or decreased in the regions that implement more ambitious emission mitigation. If the acting region (like the EU) reduces gas consumption, other regions might use this gas as a substitute for carbon-intensive coal. This cause–effect chain reduces carbon leakage and can even result in negative carbon leakage. But, if the other regions in turn use more coal to substitute for the missing gas, the carbon leakage rate increases again. A similar cascade of effects can happen, if the acting regions reduce oil, which leaks to the rest of the world where it helps to substitute coal.

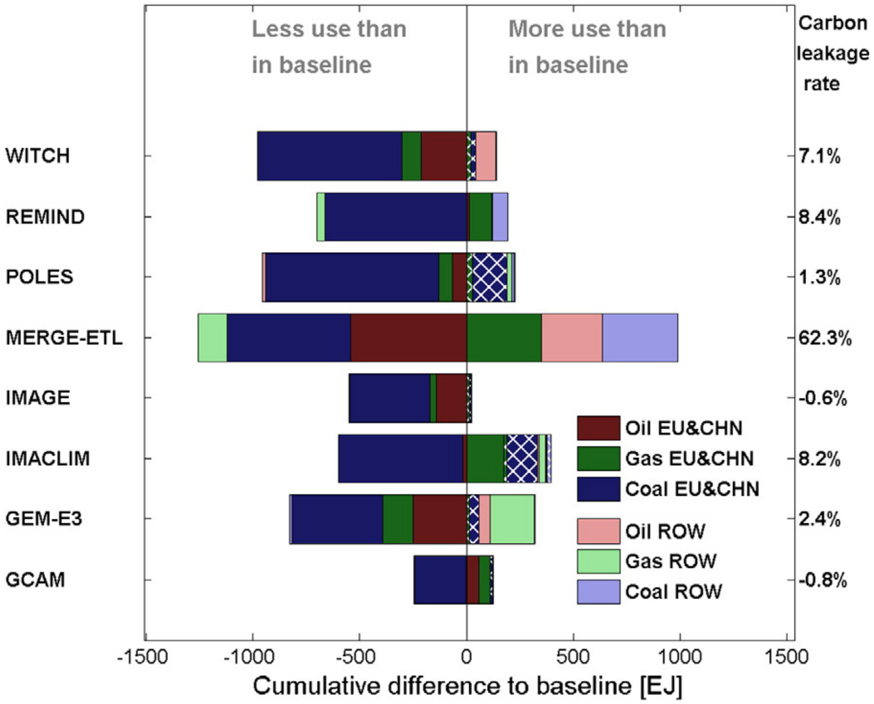

**Fig. 7.** Changes of cumulative use of fossil energy carriers 2010–30 in EU27 + China and Rest of World compared with Reference Policy baseline, when EU27 and China apply the CO2 tax of the 450 ppm-e case. Hatched bars indicate fossil fuel use in combination with CCS.

## 6. Conclusions

Policies to limit $CO_2$ emissions in the near-term and stabilize climate change in the long-term will interfere with global fossil fuel markets in the short- and the long-run. This study explores a multi-model scenario ensemble to gain insights into this interrelationship. Our analysis makes four original contributions to the scientific literature relevant for the assessment of climate change mitigation policies.

The first contribution is that we compare the short- and long-term use of coal, oil and gas without and with climate stabilization targets. We account for the use of CCS and we compare the fossil fuel consumption with the corresponding endowments. This quantification adds to the analysis highlighted by the IPCC (SPM TAR WGIII) that did not differentiate coal, oil and gas [4]. The main result is that to achieve a 450 ppm-$CO_2$eq target coal use over the 21st century has to decrease significantly and more than half of the proven reserve is left underground. Under the same scenario, oil and gas are only marginally affected in the near-term, and total use exceeds conventional reserves and non-conventional reserves in the case of oil. CCS applied in combination with coal and gas can significantly relax the constraint on fossil fuel use. This is in stark contrast with a scenario without emission limitations where coal reserves may be exhausted and non-conventional oil resources would be used in the 21st century.

The second original contribution relates to discounted fossil fuel revenues. We show that coal generates the smallest revenue, even though it is—without emission limitations—the largest source of $CO_2$ emissions. Oil and gas have much higher market prices and, consequently, their revenues are significantly higher. Despite large price uncertainties reflected in the various models, we find that climate change stabilization accelerates the secular trend of declining GDP shares of fossil fuel revenues. Models with high fossil fuel prices, in particular oil, also see large reductions of fossil fuel revenues, if climate change stabilization targets are met because the quantity reduction is also combined with a price reduction. Fossil fuel revenues can decrease by 50% due to climate change stabilization.

The third contribution addresses the deviation from the idealized approach of full ‘when’-flexibility. Starting from the case with full ‘when’-flexibility we assess short- and long-term impacts of pledges in the Copenhagen Accord on fossil fuel markets. In the short-term fossil fuel markets revert back to the pathway of a scenario without emission limitations. Coal is the fossil fuel for which the quantity change is largest, but as the price is low revenue effects are small. Though oil and gas use increase less, the gain in revenues is larger than for coal, because the prices are higher and also revert back to the baseline case. In the longer-term, fossil fuel use would need to decrease to comply with the carbon budget. The short-term distortion with higher coal use leads to strongly amplified reallocations over the rest of the century, because higher near-term emissions from coal are balanced with lower emissions from gas and oil as well as reduced use of fossils with CCS. The initial distortion is amplified even more if the energy sector suffers from a coal lock-in. This amplification can lead to double or even triple as large long-term fossil fuel re-allocation as compared to the initial distortion. However, total fossil fuel revenues over the 21st century would increase due to discounting because the short-term effect outweighs the long-term effect. Differentiating between fossil fuels, it is found that this is not necessarily the case for oil and gas, but surely for coal. The amplification of market distortions and the effect on fossil fuel revenues is novel and highly relevant for the assessment of the timing of global emission pathways over the 21st century.

The fourth contribution addresses the issue of carbon leakage from early mover action. The period of weak action might be bridged by additional action of early movers, like the EU and China in the present study, in a world that is framed by weak and fragmented mitigation policies. Carbon leakage can potentially undermine the environmental effectiveness of unilateral policies because other countries increase their emissions. Our study is the first focusing on carbon leakage via the energy channel using a broad suit of models with detailed representation of the energy sector. Our results show a large uncertainty around the carbon leakage rate, which can exceed 50%, but negative values are also possible, depending on the model and the choice of countries that play the pioneering role in climate change mitigation. We identify three main factors contributing to the variation in leakage rates. First, the baseline energy system development and the impact of early mover action on domestic fossil energy use determine the initial effect on international fossil energy markets. Generally, coal and oil use are reduced, but gas demand can increase, particularly if China moves early and substitutes coal with gas. Also, reduced domestic coal use does not necessarily increase international coal supply because of transportation costs to international markets. However, coal and gas can also be used in combination with CCS, which leads to lower emissions without increasing global supply. Second, the responsiveness of other countries to changes in fossil fuel supply differs for coal, oil and gas. Reducing consumption of internationally traded oil implies high leakage rates; the same does not hold for coal because of high transportation costs and weak carbon prices outside the pioneering countries. Third, changes in fossil fuel prices induce substitution effects in reluctant countries. In particular, increasing world supply of oil and gas can serve as a substitute for coal in non-acting regions, which reduces the overall carbon leakage and potentially causes negative carbon leakage.

These findings on leakage rates are a novelty. In 2007 the IPCC stated that carbon leakage rates vary between 5 and 20% [5]. [17] confirms this range and highlights that the competitiveness channel is more important than the energy channel. Detailed energy sector representations used in our analysis indicate a much larger uncertainty range. Negative carbon leakage results from inter-fuel substitution in non-acting countries due to changing fossil fuel prices. The cause–effect chain is fundamentally different than the line of argumentation treated in a series of papers recently published in the *American Economic Review*. The trigger for negative carbon leakage identified by [20–22] is based on the scarcity of capital that leads to the abatement resource effect (AER). If the abating country demands more of the fixed factor capital, then the non-abating country reduces total economic activity and therefore $CO_2$ emissions. Our study explains negative leakage by the combination of international fossil fuel market reallocation and inter-fuel substitution rather than resting on the assumption that capital is a fixed factor. The issue of capital market reallocation is also treated in the paper by Curras et al. in this special issue, where international capital mobility is identified as positive, though small trigger for carbon leakage [28].

In summary, when examining the effects of climate stabilization policies on fossil fuel markets, one has to consider the fundamental differences of coal, oil and gas markets. Comparing the two deviations from idealized policies to achieve climate change stabilization shows that it is important to achieve an early, comprehensive and ambitious agreement on emission stabilization to reduce emissions from coal. If some countries choose to move early to limit $CO_2$ emissions, the issue of carbon leakage arises, but the magnitude is highly uncertain and even the direction is unclear because of inter-fuel substitution induced in non-acting countries.

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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.2013.09.009.

## References

[1] I.E.A. International Energy Agency, World Energy Outlook 2012, 2012. (Paris, France).

[2] T. Barker, I. Bashmakov, et al., Mitigation from a cross-sectoral perspective, in: B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (Eds.), Climate Change 2007: Mitigation, Contribution of WGIII to the AR4 of the IPCCCambridge University Press, Cambridge, United Kingdom and New York, 2007.

[3] M. Grubb, Who's afraid of atmospheric stabilisation? Making the link between energy resources and climate change, Energy Policy 29 (2001) 837–845.

[4] IPCC, Summary for Policymakers, in: B. Metz, O. Davidson, R. Swart, J. Pan (Eds.), Climate Change 2001: Mitigation, Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate ChangeCambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2001.

[5] IPCC, Summary for Policymakers, in: B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (Eds.), Climate Change 2007: Mitigation, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate ChangeCambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007, (International Energy Agency IEA (2012) World Energy Outlook 2012. Paris, France).

[6] M. den Elzen, A.F. Hof, M. Roelfsema, The emissions gap between the Copenhagen pledges and the 2 °C climate goal: options for closing and risks that could widen the gap, Glob. Environ. Chang. 21 (2011) 733–743.

[7] T.M.L. Wigley, R. Richels, J.A. Edmonds, Economic and environmental choices in the stabilization of atmospheric CO2 concentrations, Nature 379 (1996) 240–243.

[8] F. Toth, M. Mwandosya, et al., Decision Making Frameworks, in: B. Metz, O. Davidson, R. Swart, J. Pan (Eds.), Climate Change 2001: Mitigation, Contribution of WGIII to the AR4 of the IPCCCambridge University Press, Cambridge, United Kingdom and New York, 2007.
[9] L. Clarke, J.A. Edmonds, V. Krey, R. Richels, S. Rose, M. Tavoni, International climate policy architectures: overview of the EMF22 international scenarios, Energy Econ. 31 (2009) S64–S81.
[10] O. Edenhofer, C. Carraro, J.C. Hourcarde, K. Neuhoff, G. Luderer, C. Flachsland, M. Jakob, A. Popp, J. Steckel, J. Strohschein, N. Bauer, S. Brunner, M. Leimbach, H. Lotze-Campen, V. Bosetti, E. de Cian, M. Tavoni, O. Sassi, H. Waisman, R. Crassous-Doerfler, S. Monjon, S. Dröge, H. van Essen, P. del Río, A. Türk, RECIPE: The economics of decarbonization, Potsdam-Institut für Klimafolgenforschung, Potsdam, Germany, 2009.
[11] B.C. O'Neill, K. Riahi, I. Keppo, Mitigation implications of mid-century targets that preserve long-term climate policy options, PNAS 107 (2010) 1011–1016.
[12] J. Rogelj, D.L. McCollum, B.C. O'Neill, K. Riahi, 2020 emissions levels required to limit warming to below 2 °C, Nat. Clim. Chang. 493 (2013) 79–83, http://dx.doi.org/10.1007/s10584-013-0939-5.
[13] D.L. McCollum, N. Bauer, K. Calvin, A. Kitous, K. Riahi, Fossil resource and energy security dynamics in conventional and carbon-constrained worlds, Clim. Chang. (2013), http://dx.doi.org/10.1007/s10584-013-0901-6.
[14] N. Bauer, I. Mouratiadou, G. Luderer, L. Baumstark, R.J. Brecha, O. Edenhofer, E. Kriegler, Global fossil energy markets and climate change mitigation—an analysis with REMIND, Clim. Chang. (2013)(in press).
[15] E. Kriegler, K. Riahi, N. Bauer, J. Schwanitz, et al., Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy, Technol. Forecast. Soc. Chang. 90 (2015) 24–44(this issue).
[16] M. Hoel, Efficient climate policy in the presence of free riders, J. Environ. Econom. Manag. 27 (1994) 259–274.
[17] C. Böhringer, E.J. Balistreri, T.F. Rutherford, The role of border carbon adjustment in unilateral climate policy: overview of an Energy Modeling Forum study (EMF 29), Energy Econ. Suppl. 2 (2012) S97–S110.
[18] J. Burniaux, J. Oliveira-Martins, Carbon emission leakages: a general equilibrium view, OECD Economics Department Working Paper 242, OECD Economics Department, Paris, France, 2000.
[19] C. Böhringer, A. Lange, T.F. Rutherford, Optimal emission pricing in the presence of international spillovers: decomposing leakage and terms-of-trade motives, NBER Working Paper 158992010.
[20] K. Baylis, D. Fullerton, D.H. Karney, Leakage, welfare, and cost-effectiveness of carbon policy, Am. Econ. Rev. 103 (2013) 332–337.
[21] J.C. Carbone, Linking numerical and analytical models of carbon leakage, Am. Econ. Rev. 103 (2013) 326–331.
[22] N. Winchester, S. Rausch, A numerical investigation of the potential for negative emissions leakage, Am. Econ. Rev. 103 (2013) 320–325.
[23] H.H. Rogner, R. Aguilera, et al., Energy Resources and Potentials. In Global Energy Assessment, in: T.B. Johansson, A. Patwardhan, N. Nakicenovic, L. Gomez-Echeverri (Eds.), Cambridge University Press, Cambridge MA, 2012, (Chapter 7).
[24] K. Riahi, E. Kriegler, N. Johnson, C. Bertram, M. den Elzen, J. Eom, M. Schaeffer, et al., Locked into Copenhagen pledges—implications of short-term emission targets for the cost and feasibility of long-term climate goals, Technol. Forecast. Soc. Chang. 90 (2015) 8–23 (in this issue).
[25] C. Bertram, N. Johnson, G. Luderer, K. Riahi, M. Isaac, J. Eom, Carbon Lock-in through capital stock inertia associated with weak near-term climate policies, Technol. Forecast. Soc. Chang. 90 (2015) 62–72 (in this issue).
[26] B.P. British Petroleum, Statistical Review of World Energy, http://www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481 2012(accessed August 1, 2012).
[27] L. Paroussos, P. Fragkos, P. Capros, K. Fragkiadakis, Assessment of carbon leakage through the industry channel: the EU perspective, Technol. Forecast. Soc. Chang. 90 (2015) 204–219.
[28] T.A. Curras, N. Bauer, E. Kriegler, J. Schwanitz, G. Luderer, T. Aboumahboub, A. Giannousakis, J. Hilaire, Carbon leakage in a fragmented climate regime: the dynamic response of global energy markets, Technol. Forecast. Soc. Chang. 90 (2015) 192–203.

**Nico Bauer** is leader of the Energy Resources and Technologies Group in the Sustainable Solutions research domain at Potsdam Institute for Climate Impact Research (PIK).

**Valentina Bosetti** is climate change topic leader and a modeler for the Sustainable Development Programme at FEEM. Since 2012, she is also an associate professor at the Department of Economics, Bocconi University.

**Meriem Hamdi-Cherif** is a researcher at the International Research Centre on Environment and Development (CIRED, France). Her work focuses on the IMACLIM-R modeling framework and climate policies and development.

**Alban Kitous** is Scientific Officer at the European Commission Joint Research Center. He is a specialist in energy economic modeling and policy assessment.

**David McCollum** is a research scholar in the Energy Program at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria.

**Aurélie Méjean** is a research fellow at the International Research Centre on Environment and Development (CIRED, France). She is a member of the energy-economy-environment modelling team.

**Shilpa Rao** is a research assistant in the Energy Program at the International Institute for Applied Systems Analysis (IIASA). Her research includes energy-economic modeling, technology assessment and multi greenhouse gas scenarios.

**Hal Turton** leads the Energy Economics Group at the Paul Scherrer Institute (PSI). His research focuses on scenario analysis of global and European energy systems development, integration of energy and economic models, and technology assessment.

**Leonidas Paroussos** is a senior researcher at the E3M-Lab/ICCS and he is experienced in climate change policy assessment using general equilibrium models, environmental economics and energy analysis.

**Shuichi Ashina** is a researcher focusing on energy-economy-environmental systems modeling at the Center for Social and Environmental Systems Research of the National Institute for Environmental Studies.

**Katherine Calvin** is a research economist at the Pacific Northwest National Laboratory's Joint Global Change Research Institute. Her research focuses on model development and scenario analysis with both the Second Generation Model (SGM) and the Global Change Assessment Model (GCAM).

**Kenichi Wada** is a senior researcher at Systems Analysis Group of the Research Institute of Innovative Technology for the Earth (RITE, Japan).

**Detlef P. van Vuuren** is a senior researcher at PBL Netherlands Environmental Assessment Agency—working on integrated assessment of global environmental problems. He is also a professor at the Copernicus Institute for Sustainable Development at Utrecht University.