Technological Forecasting & Social Change 90 (2015) 24–44

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy

Elmar Kriegler [a,*], Keywan Riahi [b], Nico Bauer [a], Valeria Jana Schwanitz [a], Nils Petermann [a], Valentina Bosetti [c], Adriana Marcucci [d,e], Sander Otto [f], Leonidas Paroussos [g], Shilpa Rao [b], Tabaré Arroyo Currás [a], Shuichi Ashina [h], Johannes Bollen [i], Jiyong Eom [j,1], Meriem Hamdi-Cherif [k], Thomas Longden [c], Alban Kitous [l,2], Aurélie Méjean [k], Fuminori Sano [m], Michiel Schaeffer [n], Kenichi Wada [m], Pantelis Capros [g], Detlef P. van Vuuren [f,o], Ottmar Edenhofer [a,p,q]

[a] *Potsdam Institute for Climate Impact Research, Potsdam, Germany*
[b] *International Institute for Applied Systems Analysis, Laxenburg, Austria*
[c] *Fondazione Eni Enrico Mattei, Milan, Italy*
[d] *Paul Scherrer Institute, Villigen, Switzerland*
[e] *ETH Zurich, Zurich, Switzerland*
[f] *Utrecht University, Copernicus Institute for Sustainable Development, Utrecht, The Netherlands*
[g] *Institute of Communication and Computer Systems, Athens, Greece*
[h] *National Institute of Environmental Studies, Tsukuba, Japan*
[i] *CPB Netherlands Bureau for Economic Policy Analysis, The Hague, The Netherlands*
[j] *Pacific Northwest National Laboratory's Joint Global Change Research Institute, College Park, United States*
[k] *Centre International de Recherche sur l'Environnement et le Développement, Paris, France*
[l] *European Commission Joint Research Centre, Sevilla, Spain*
[m] *Research Institute of Innovative Technology for the Earth, Kizugawa-shi, Japan*
[n] *Climate Analytics, Berlin, Germany*
[o] *PBL Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands*
[p] *Technische Universität Berlin, Berlin, Germany*
[q] *Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany*

ARTICLE INFO

Article history:
Received 28 June 2013
Received in revised form 21 September 2013
Accepted 28 September 2013
Available online 11 March 2014

Keywords:
Climate change mitigation
Integrated assessment models
Climate change economics
Carbon leakage
European Union
Regional climate policies

ABSTRACT

This study explores a situation of staged accession to a global climate policy regime from the current situation of regionally fragmented and moderate climate action. The analysis is based on scenarios in which a front runner coalition – the EU or the EU and China – embarks on immediate ambitious climate action while the rest of the world makes a transition to a global climate regime between 2030 and 2050. We assume that the ensuing regime involves strong mitigation efforts but does not require late joiners to compensate for their initially higher emissions. Thus, climate targets are relaxed, and although staged accession can achieve significant reductions of global warming, the resulting climate outcome is unlikely to be consistent with the goal of limiting global warming to 2 degrees. The addition of China to the front runner coalition can reduce pre-2050 excess emissions by 20–30%, increasing the likelihood of staying below 2 degrees. Not accounting for potential co-benefits, the cost of front runner action is found to be lower for the EU than for China. Regions that delay their accession to the climate regime face a trade-off between reduced short term costs and higher transitional requirements due to larger carbon lock-ins and more rapidly increasing carbon prices during the accession period.

---

* Corresponding author at: Potsdam Institute for Climate Impact Research (PIK), Telegraphenberg A31, 14473 Potsdam, Germany. Tel.: +49 331 288 2616.
E-mail address: kriegler@pik-potsdam.de (E. Kriegler).

[1] Now at Sogang University, Seoul, South Korea.

[2] The views expressed are purely those of the author and may not in any circumstances be regarded as stating an official position of the European Commission.

http://dx.doi.org/10.1016/j.techfore.2013.09.021

1. Introduction

Climate change is one of the great global policy challenges of our time. It is increasingly recognized that unabated climate change can lead to large impacts on human societies [1,2]. At the same time, slow progress in international climate negotiations has given rise to skepticism about the prospect of global cooperative action on climate change. Given the scope of the coordination challenge, emphasis has shifted from global cooperative action to regional climate action and to the integration of other priorities such as energy security and development policies. Yet, the quest for a more comprehensive international climate treaty with binding targets continues. After a failure at the Copenhagen climate conference in 2009, negotiators agreed on a new attempt to adopt a global treaty to come into effect by 2020 [3]. Whether the so-called Durban platform for enhanced action will fare any better than the previous attempt is highly uncertain. Yet, targeting greenhouse gas emissions globally has clear advantages. From an economic point of view, it is most efficient to exploit the cheapest abatement option in the sector and region at the margin. It is total global emissions which matter with respect to limiting atmospheric greenhouse gas (GHG) concentrations and global mean temperature.

Even though the advantages of global cooperation are evident, the world may be locked into moderate and fragmented climate action due to the institutional, ethical and political challenges posed by the need for international coordination, transfers and incentives. Recent studies have shown that an extrapolation of the current national pledges over the 21st century is likely to lead to warming of more than 3 degrees by the end of the century and further warming thereafter [4,5]. In light of this, the present paper aims at investigating how effective a group of countries might be in leading the way with stringent mitigation action even if the rest of the world joins the effort only decades later. There is literature in support of the idea that in situations of cooperation problems involving a public good, a leader setting a good example can play a role [6,7]. Such unilateral climate action might both reduce uncertainty about the mitigation costs and, at the same time, build credibility, which is an important element in international coordination problems [8–10]. In addition, it might also address concerns related to historical responsibility, frequently raised at the negotiation tables by developing countries [11].

This paper presents a multi-model exploration of staged accession scenarios to a global climate regime conducted within the AMPERE project. It focuses on the EU as a candidate for pioneering stringent climate action. The EU has adopted a 20% emission reduction target for 2020 relative to 1990 as part of its climate and energy package [12] and has agreed to commit to the 20% target in the second commitment period of the Kyoto protocol. It has established the worlds' largest emissions trading system and has implemented a number of additional climate policies at the national level. The EU has also discussed the unilateral strengthening of its reduction target to 30% by 2020, and established a “Roadmap for moving to a competitive low carbon economy for 2050” (short: EU Roadmap) that envisions 80% emission reduction by 2050 [13].

The main research question is concerned with the stakes of adopting the EU Roadmap without an international climate agreement in place. The study considers two opposite possible outcomes: either the rest of the world makes a transition to an ambitious global climate regime in the period 2030–2050 (Success), or the EU has to return to a more moderate climate policy reference case after 2030 if it becomes clear that the rest of the world does not increase its level of ambition (Reconsideration). In particular, we investigate the following questions:

a) In the case of successful staged accession, what are the climate outcome and the mitigation costs relative to both the reference case and the ideal case of immediate global cooperation?
b) In both cases (success and reconsideration), how does the asymmetry between mitigation efforts by the front runners and other regions impact regional emissions and costs due to carbon leakage, technology spillover and carbon lock-ins?

The study also explores the case of a front runner coalition with two major players leading the way. A coalition between the EU and China was chosen for several reasons. First, China may face notable climate change impacts, e.g. in the area of freshwater resources that are already strained in some regions [14]. It thus has a strong incentive to mitigate climate change. Second, China is suffering from a major air pollution problem and thus can expect to reap significant co-benefits from the reduction of fossil fuel use, particularly coal [15,16]. Third, China is the world's largest emitter, and the stringency of its climate action will have a strong impact on global emissions and the global energy sector. This gives it high visibility in international climate negotiations. Fourth, China has been very active in enacting a number of domestic climate and energy policies and is expected to adopt more in the future [17,18]. Although the case of an EU–China coalition does not reflect the current status of international climate negotiations, a bilateral dialog on climate policy issues has progressed [19]. Finally, the investigation of an EU–China climate coalition permits us to study how the impacts of advanced mitigation efforts differ between two regions with substantially different economic profiles.

The study builds on a comparison of results from 11 energy–economy and integrated assessment models (IAMs). Such models have been extensively used to explore mitigation pathways which meet long-term climate targets (e.g. [20,21]). Previous energy–economy and IAM intercomparison exercises have investigated idealized policy settings such as global carbon tax scenarios [22] and immediate cooperative action to reach stabilization targets in the range between 450 and 650 ppm CO_2e [23,24,25]. Previous exercises have also reviewed limited policy situations with constrained technology availability [24,26] and delayed and fragmented action [4,23,27,28]. [23] investigated a staged accession scenario with two groups of countries joining the industrialized countries over the period 2030–2070. The analysis highlighted the difficulty to reach stringent stabilization targets in such a setting. [28] focused on delay until 2020 and identified benefits for early movers if the long term target is maintained.

This study considers two different long-term climate targets (450[3] and 550 ppm CO_2e) as guiding principles for long term climate action. Contrary to the previous comparison studies on staged accession [23,28], we do not assume that the climate targets and their associated greenhouse gas

---

[3] It has been shown that the lower target of 450 ppm CO_2e has a large probability of keeping global mean warming below 2°C since preindustrial times [29]. The 2 degree target was recognized by the international climate negotiations as consistent with the goal to avoid dangerous anthropogenic interference with the climate system [30].

emissions budgets for the 21st century are necessarily met even if most world regions join the climate regime at a later point in time. Whereas the early movers contribute their part to meeting the climate target, the acceding regions harmonize their carbon prices with those of the early movers only after considerable delay. This delay results in excess emissions compared to immediate global cooperation and thus is associated with a relaxation of the long-term climate target depending on the extent of this initial excess.

The assumption of target relaxation due to delay and the inclusion of reconsideration scenarios constitute a new contribution to the literature. The scenario setup also allows us to study the countering impact of greenhouse gas leakage during an initial period of fragmented action in a dynamic and long-term setting, thus adding to the literature on short-term leakage effects until 2020 [31]. In summary, the study responds to the need for a deeper exploration of the current climate policy situations in long-term mitigation scenarios addressing the question of how to bridge the gap between short-term commitments and long-term aspiration in international climate policy negotiations.

This overview article is accompanied by a series of papers exploring various perspectives of the staged accession scenarios in greater depth. [32] provides an in-depth look into the energy sector implications and co-benefits of EU front runner action. [33] explores the leakage effects on global fossil energy markets, while [34] reviews the role of technology diffusion in the electricity sector. [35] investigates the climate response in greater detail. Individual model analyses explore the effect of coalition size on leakage dynamics [36] and add further perspective on leakage effects via the industry channel [37] and the land use sector [38]. This paper is structured in seven sections. The following section introduces the scenario design and the participating models. Section 3 explores the effect of near term climate policy fragmentation and technology targets on carbon prices. This is followed by a discussion of global mitigation stringency and economic costs in staged accession scenarios. Section 5 provides a regional perspective and focuses on the trade-offs faced by front runner and latecomer regions. Section 6 investigates the role of carbon leakage and technology diffusion in the near term, summarizing a set of results from the companion papers. Section 7 concludes.

2. Methods

The findings of this study are based on a set of coordinated scenario runs from 11 global energy–economy and integrated assessment models. It is one in a series of global model intercomparison studies conducted within the AMPERE project. The series also includes a diagnostic exercise [39] and a

Table 1
Participating models in the study. Coverage of low carbon energy supply options is based on a count of low carbon energy conversion routes presented in [39]. The classification of models into general (GE) and partial equilibrium (PE) models with low, medium and high response to carbon pricing was also developed in [39].

Model name	Institute	Equilibrium concept	Solution dynamics	Time horizon	Coverage of low carbon energy supply options [39]	Land use sector representation	Coverage of greenhouse gases	Classification in [39]
DNE21+ [41]	RITE, Japan	Partial	Intertemporal optimization	2050	High	MACs for land use emissions	All GHGs and other radiative agents	PE-low response
GCAM [42]	PNNL, USA	Partial	Recursive dynamic	2100	High	Endogenous land use dynamics, afforestation	All GHGs and other radiative agents	PE-high response
GEM-E3 [43]	ICCS, Greece	General	Recursive dynamic	2050	Low	MACs for land use emissions	Kyoto gases	GE-low response
IMACLIM [44]	CIRED, France	General	Recursive dynamic	2100	Medium	None	CO_2 from fossil fuel combustion and industry	GE-low response
IMAGE/TIMER [45]	PBL/UU, The Netherlands	Partial	Recursive dynamic	2100	High	Endogenous land use dynamics	All GHGs and other radiative agents	PE-high response
MERGE-ETL [46]	PSI, Switzerland	General	Intertemporal optimization	2100	High	MACs for land use emissions	All GHGs and other radiative agents	GE-high response
MESSAGE-MACRO [47]	IIASA, Austria	General	Intertemporal optimization	2100	High	MACs for land use emissions, Afforestation	All GHGs and other radiative agents	GE-high response
POLES [48]	JRC IPTS, EU// EDDEN, France	General	Recursive dynamic	2100	High	None	Kyoto gases from fossil fuel combustion and industry	PE-medium response
REMIND [49]	PIK, Germany	General	Intertemporal optimization	2100	High	MACs for land use emissions	All GHGs and other radiative agents	GE-high response
WITCH [50]	FEEM, Italy	General	Intertemporal optimization	2100	Low	MACs for land use emissions	Kyoto gases	GE-low response
WorldScan2 [51]	CPB, The Netherlands	General	Recursive dynamic	2050	Low	MACs for land use emissions	CO_2, CH4, N2O	

study on the consequences of weaker short term action for meeting long term stabilization targets [40].

2.1. Participating models

The participating energy–economy models and IAMs originate from Europe, the United States, and Japan and are listed in Table 1. All models have global coverage with varying disaggregation of world regions. The set of models can be broadly grouped into four different categories spanned by partial (PE) or general equilibrium (GE) models, and dynamic recursive (myopic) or intertemporal optimization (foresight) models. However, models also differ in numerous other ways. The technological detail in the energy sector, the substitutability of energy carriers and the representation of greenhouse gases are other key factors influencing model results. GDP and population assumptions were harmonized across models to facilitate the analysis of model differences (see Section S3.4 in the supplementary online material (SOM) for further details). The analysis of model differences is also aided by a set of diagnostic indicators for model behavior that were developed by [39].

The differences in model structure and assumptions reflect different choices of modelers on how to best approach the analysis by mitigation pathways. We want to point out that this diversity in model structure and assumptions is not a drawback, but a feature of model comparisons, since it allows us to explore the associated range of uncertainties. However, it is important to recognize that the breadth of assumptions made by this set of models does not necessarily cover the entire range of possibilities.

The differences in the disaggregation of world regions pose a challenge for the comparison of results across models. Following existing practice in previous studies, results are compared on a set of harmonized regions to which the closest (set of) native model region(s) is mapped for each model. Thus it is important to keep in mind that regional results from different models can refer to somewhat different regional definitions (see Section S2.2 in the SOM for further details). Most relevant for this study are deviations for the EU, China and Rest Of the World (= world without EU and China) regions. Notably, the EU region of GCAM, IMACLIM and MESSAGE includes Turkey, and the China region of MESSAGE and MERGE-ETL includes formerly centrally planned Southeast Asian economies. Thus, regional EU, China, and ROW results from these models allow for only a limited comparison with results from the other models.

2.2. Scenario design

The analysis is based on a set of scenarios that are characterized by different climate action for front runner regions – the EU alone or the EU and China jointly – and the rest of the world. The front runners adopt ambitious climate policies as early as 2015 (depending on the first model time step following 2010) while the other regions continue to follow a reference policy characterized by moderate and fragmented action. The front runner scenarios hit a crossroads in 2030 where it is decided whether or not their action was effective in inducing the rest of the world to transition to a global climate policy regime by 2050. Thus, we can group these scenarios into two sets — staged accession and reconsideration (of stringent climate action) scenarios. The full scenario setup is summarized in Table 2. In the following, we will briefly discuss the individual scenario classes. Further information on the scenario design is given in Section S3 of the SOM.

2.2.1. No-policy baseline scenario

The no-policy baseline scenario (Base) represents a counterfactual case in which no future policies dedicated to climate change mitigation are pursued. Energy policies like fossil fuel taxes and subsidies that are not related to climate policy may still apply depending on individual model assumptions.

2.2.2. Reference policy scenario

The reference policy (RefPol) scenario tries to capture main elements of the current climate policy landscape by including emission reduction commitments and renewable or nuclear energy technology targets at the level of 25 world regions and major emitting countries. The emission targets are mostly based on the unconditional Copenhagen pledges of countries. Beyond the 2020 time horizon, regions are assumed to continue with emission reductions that sustain their average emissions intensity improvements at a rate that it is roughly consistent with their pre-2020 action or slightly strengthened for regions without emission targets until 2020. The technology targets include renewable energy portfolio standards and capacity targets for renewable and nuclear energy that are implemented through minimum capacity and share constraints, or direct technology policies. As an exception, the IMACLIM model adjusted regional carbon prices to achieve the technology targets. All other policy and input assumptions were unchanged between the no policy baseline and the RefPol scenario with the exception of the IMACLIM model. IMACLIM accompanied carbon pricing with policy measures aimed at controlling the long-term dynamics of transport-related emissions in all climate policy scenarios [52], and measures to make labor markets more flexible [53]. A detailed definition of the reference policy scenario is given in Section S3.1 of the SOM.

2.2.3. Climate policy benchmark scenarios

The benchmark immediate action scenarios aim to reach atmospheric GHG concentrations at levels of 450 ppm (Scenarios *450*, *CF450*) and 550 ppm CO_2e (Scenarios *550*, *CF550*) by the end of the century. Global cooperation toward these goals starts immediately. Scenarios 450 and 550 include the technology targets of the reference policy scenario while the counterfactual scenarios CF450 and CF550 do not. To harmonize targets between models capturing different baskets of radiative agents and to remove uncertainties in translating forcing levels into cumulative GHG emissions, models were provided with a cumulative CO_2 budget for the 21st century as a long-term target (1500 $GtCO_2$ and 2400 $GtCO_2$ for the period 2000–2100 and the 450 and 550 ppm CO_2e targets, respectively). Further details can be found in Section S3.2 of the SOM.

2.2.4. Staged accession scenarios

In this scenario set, the EU (or China and the EU, short: CE) as front runner successfully motivates the other regions to join an ambitious climate regime in 2030. As a single front runner, the EU adopts the climate roadmap immediately, while the

Table 2
Scenario design of the AMPERE study on staged accession scenarios.

Scenario type	Short name	Global target	Tech. targets	Regions	Carbon price until 2030	Carbon price after 2030-50 transition
Reference policy	RefPol	None	Yes	All	Derived from regional targets (where existing)	
No-policy baseline	Base	None	No	All	None	
Climate policy benchmark scenarios	450	450 ppm	Yes	All	Globally harmonized to meet 450 ppm target	
	550	550 ppm	Yes	All	Globally harmonized to meet 550 ppm target	
	CF450	450 ppm	No	All	Globally harmonized to meet 450 ppm target	
	CF550	550 ppm	No	All	Globally harmonized to meet 550 ppm target	
Staged accession scenarios	450P-EU	None	Yes	EU (front runner)	Price derived from EU roadmap targets	Globally harmonized price from *450* scenario
				Other regions	Regional prices from *RefPol*	
	450P-CE	None	Yes	EU + China (front runners)	Price from scenario *450*	Globally harmonized price from *450* scenario
				Other regions	Regional prices from *RefPol*	
	CF450P-EU	None	No	EU (front runner)	Price derived from EU roadmap targets	Globally harmonized price from *CF450* scenario
				Other regions	None	
	550P-EU	None	Yes	EU (front runner)	Price derived from EU roadmap targets	Globally harmonized price from *550* scenario
				Other regions	Regional prices from *RefPol*	
Reconsideration scenarios	RefP-EUback	None	Yes	EU (front runner)	Price derived from EU roadmap targets	Regional prices from *RefPol*
				Other regions	Regional prices from *RefPol*	
	RefP-CEback	None	Yes	EU + China (front runners)	Price from scenario *450*	Regional prices from *RefPol*
				Other regions	Regional prices from *RefPol*	
	Base-EUback	None	No	EU (front runner)	Price derived from EU roadmap targets	None
				Other regions	None	

others follow their reference policy (scenarios 450P-EU/550P-EU) or – as a sensitivity case – no climate policy at all (scenario CF450P-EU) until 2030. The EU climate roadmap is specified in terms of −25%, −40% and −80% GHG emission reductions targets in 2020, 2030 and 2050, respectively, relative to 1990 (approx. −20%, −35%, and −75% relative to 2005). After 2030, the carbon price converges in all regions, including the EU, from the 2030 levels to the 450 ppm (450P-EU/CF450P-EU) or 550 ppm (550P-EU) carbon price in 2050. The 450 ppm and 550 ppm carbon prices are adopted from the benchmark 450 and 550 scenarios. Prior to the global carbon price convergence, the rest of he world implements the reference policy carbon pricing (deduced from the RefPol scenario) to allow for GHG leakage effects in the period of fragmented action until 2050. In the case of an EU and China front runner coalition (450P-CE), both adopt the 450 ppm carbon price immediately and continue on this trajectory over the 21st century.

2.2.5. Reconsideration scenarios

In this set of scenarios, the front runners are unable to motivate other regions to transition to a more ambitious global climate regime, and as a result reconsider their own stringent mitigation action. Concretely, they transition back to the reference policy over the period 2030 to 2050, while the others follow the reference policy throughout the 21st century (*RefP-EUback/CEback*). In a sensitivity case, others adopt no climate policy at all and the EU phases out its climate action during 2030 to 2050 (*Base-EUback*).

2.2.6. Implementation of scenario design

8 of 13 scenarios were mandatory to run for all models (RefPol, Base, 450, 550, CF450, CF550, 450P-EU, RefP-EUback). The remaining five staged accession and reconsideration scenarios were optional sensitivity cases. The implementation of scenarios by participating models is documented in Section S3.5 of the SOM.

2.3. Derivation of climate outcomes

The GHG concentration, radiative forcing and temperature trajectories that result from the emissions scenarios in this study have been calculated with the atmospheric chemistry-climate model MAGICC [54]. Usually, model comparisons use the reported forcing and climate information from participating modeling teams. The approach used here has the advantage of providing a unified treatment of carbon cycle and climate system uncertainty – as it has been shown that these factors differ greatly across models [55] – and offers the possibility to generate climate information for model scenarios that do not provide it endogenously. MAGICC generates probabilistic climate projections based on a multi-variate probability distribution for atmospheric chemistry and climate system parameters [56]. The implementation of the approach in the AMPERE context is described in [35].

3. Fragmented moderate mitigation action

Several regions in the world have adopted some type of climate policy by now and/or pledged to reduce their emissions by 2020. In addition, targets to support the deployment of clean energy have been implemented in a number of countries. Ambitious climate action should therefore be measured not only against a counterfactual baseline without climate policy (Base scenario) but also compared with a reference case of regionally fragmented action at the current level of ambition. The RefPol scenario tries to capture such a reference development based on existing or planned policies. It aims to conceptualize a situation of a continued stalemate in international climate negotiations where countries continue with their currently pursued or slightly strengthened rates of emissions intensity improvement throughout the 21st century.

As a robust result across models, we find that counterfactual baseline emissions continue to rise over the 21st century, while emissions in the reference policy case peak around 2050 and return to roughly present-day emissions levels by 2100. This leads to a radiative forcing in the range of 5.5–6.5 W/m^2 in 2100 and rising thereafter. While lower than the counterfactual no-policy baseline, this is still inconsistent with the goal of long-term climate stabilization (see also [4,5]). In the near term, significant reductions in emissions are observed in the RefPol scenario compared to the Base scenario as a result of both technology policies and emission targets. Renewable-based electricity generation in the RefPol scenario is seen to increase by 10%–50% across all models compared to the counterfactual scenario in the 2010–2030 period. Despite the limited time horizon of technology-related policies, in many models renewable-based electricity generation is still higher in RefPol compared to Base in the 2030–2100 period, thus contributing to lowering of emissions in the long term.

The technology targets are also seen to have an impact on the 450 and 550 climate mitigation scenarios. In the 2020–2050 period, the scale of zero carbon energy is larger in these scenarios than in the corresponding policy cases where no specific technology targets are imposed (CF450 and CF550). However, it is important to note that the differences across the sets of scenarios are much more limited in the longer term, thus indicating the dominant impact of strong carbon pricing signals through the climate target. This is also reflected in the corresponding investments in electricity supply, which in the 450 and 550 climate scenarios compared to the CF mitigation cases are found to be higher in the 2005–2050 period but lower in the second half of the century. These findings are consistent with a number of studies [57,58] that technology policies could have an important role with regards to development and uptake of zero-carbon technologies in the shorter term but that in the longer term, strong carbon pricing mechanisms will be necessary to ensure efficient reductions in GHG emissions.

Fig. 1 compares the level of carbon prices in the year 2030 in the reference policy case across regions. We recall that carbon prices are imposed in addition to the technology targets for the year 2020. Large variations in carbon price projections exist between models. These variations persist even if carbon prices are normalized to corresponding prices in the 450 ppm CO_2e benchmark scenario. The large model differences are due to several reasons. First, carbon prices in the 2020 to 2030 time period reflect the stringency of short term emission reductions that are required in addition to the impact of increased clean energy deployment. Both sets of policies interact in that carbon prices increase the demand for clean energy and in that technology targets may reduce emissions. The extent to which carbon prices are affected by the technology targets depends on model structures and the availability of mitigation options. Second, carbon prices are also impacted by the diversity of baseline assumptions across models, as in regions where emission targets are defined relative to 1990 or 2005 emissions levels, higher baseline emissions require more mitigation effort. Third, different regional definitions associated with the harmonized study regions may also play a role.

While in regions like China, Russia and – with the exception of one model – India, RefPol emission targets are not found to be particularly binding (after including the impact of technology targets), in other regions like the EU, Latin America and USA, stringent targets imply high carbon prices and are found in some models to result in carbon prices that exceed those of the 550 or even 450 scenario in the 2010–2030 period. Thus in some models, the short-term emission targets in these regions exert more pressure than the long-term global climate targets with their temporal flexibility.

4. The global perspective: mitigation stringency and costs of staged accession to a global climate policy regime

This section describes the global outcomes of the staged accession scenarios in which the EU or the EU and China act as front runners to induce the rest of the world to eventually join climate policy efforts exceeding the reference policy. We compare these outcomes with global outcomes of baseline, reference policy and immediate action cases. What global costs and what benefits in terms of avoided climate change emerge in the staged accession scenarios? And what are the consequences of inability to persuade others to follow?

4.1. Emission outcomes

As shown in Table 3, the mitigation stringency differs markedly between staged accession scenarios and the reference

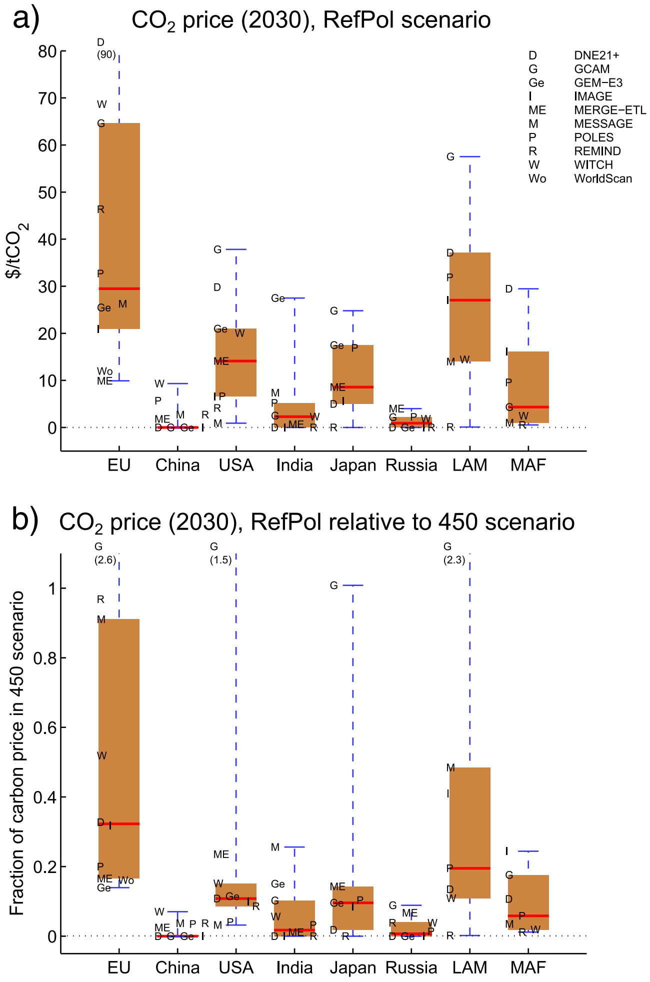


Fig. 1. Carbon price in the year 2030 in the reference policy scenario for different regions. LAM refers to Latin America, MAF to Middle East and Africa. Panel (a) shows absolute values, and Panel (b) shows relative prices as a fraction of the carbon price in the 450 ppm CO_2e immediate action case. The panel includes only those models that implemented explicit technology policies in addition to carbon pricing. For some regions, GCAM calculates carbon prices that are 2.6 (EU), 1.5 (USA), and 2.3 (LAM) times higher than in the 450 ppm scenario.

policy scenario. By 2100, the reference policy results in substantially higher cumulative emissions than the staged accession and immediate action scenarios — particularly with regards to long-lived CO_2 emissions. The gap is already significant for the period 2010–2050 and widens thereafter. By contrast, the difference in cumulative emissions between the 450 and 550 ppm CO_2e cases is much smaller.

Staged accession will lead to larger cumulative emissions than the immediate action benchmark case because it assumes the global adoption of the identical carbon price by 2050 rather than today. As shown in Table 3, this delay leads to 225–450 Gt higher fossil fuel and industry CO_2 emissions over the 21st century. The size of the front runner coalition (450P-EU vs 450P-CE) or the initial level of climate policy in the rest of the world (450P-EU vs. CF450P-EU) has a smaller impact on cumulative emissions when aggregated over the entire century, although clear differences are visible until 2050. Table 3 also shows that while staged accession to 450 ppm carbon pricing fails to deliver the full emission reductions that would emerge in the 450 immediate action case, it still reduces emissions more than in the 550 ppm CO_2e benchmark scenario.

If the front runner region cannot motivate others to adopt more ambitious climate action (reconsideration scenarios), the emission outcome is mostly determined by the reference climate policy that is implemented in the rest of the world and to which the front runner reverts after 2030. Over the 21st century, the additional mitigation effort until 2030 in the front runner region does not have a significant impact on cumulative emissions relative to the reference case. Thus, in the case of a failed attempt to achieve stringent global climate action the climate benefit from initially more ambitious action by some countries is negligible.

4.2. Reductions in global warming

The climate outcome of the different scenarios scales with the 21st century greenhouse gas emissions budgets. Across the ensemble of model scenarios, global mean warming by

Table 3
Global GHG emissions, atmospheric concentrations, and temperature outcomes in the baseline, reference policy, immediate action and staged accession scenarios. The emissions and climate outcomes of the reconsideration scenarios RefP-EUback, RefP-CEback and Base-EUback are very close to the reference policy (with the exception of emissions until 2050) and are not listed separately. Numbers correspond to the median and the full range across the scenarios (in parentheses). Temperature values in square brackets include the full climate system uncertainty (2σ range) around a mean climate sensitivity of 3 °C as derived from MAGICC for each emissions scenario. All models reported the Baseline, RefPol, 550, 450 scenarios, and all but IMACLIM the 450P-EU scenario. Model samples for the optional additional staged accession scenarios are smaller: 450P-CE (GCAM, GEM-E3, IMACLIM, IMAGE, MERGE-ETL, POLES, REMIND, and WITCH), CF450P-EU (GCAM, MERGE-ETL, POLES, REMIND, and WITCH) and 550P-EU (IMACLIM, MERGE-ETL, POLES, REMIND, and WITCH). Note that for the climate simulations, emissions were harmonized to the same base year using inventories from [59,60].

Scenario	Cumulative CO_2 fossil fuel and industry emissions	Cumulative Kyoto gas emissions	Cumulative CO_2 fossil fuel and industry emissions	Cumulative Kyoto gas emissions
	(2010–2050)	(2010–2050)	(2010–2100)	(2010–2100)
	$GtCO_2$	$GtCO_2e$	$GtCO_2$	$GtCO_2e$
Baseline	2017 (1843–2295)	2850 (2279–3214)	5926 (5058–8129)	7991 (6400–10333)
RefPol	1761 (1608–1867)	2469 (2032–2623)	4066 (3896–4906)	5493 (4603–6524)
550P-EU	1617 (1461–1675)	2198 (1695–2384)	2285 (1960–2521)	3287 (2584–3619)
550	1380 (1248–1776)	2019 (1460–2420)	2025 (1804–2160)	3251 (2330–3643)
CF450P-EU	1555 (1327–1784)	2250 (1628–2605)	1556 (1267–1767)	2845 (1885–3287)
450P-EU	1418 (1174–1652)	2155 (1500–2289)	1499 (1134–1827)	2756 (1732–3071)
450P-CE	1338 (1055–1619)	2010 (1343–2252)	1341 (1097–1520)	2694 (1562–2793)
450	1092 (975–1627)	1689 (1084–2261)	1116 (913–1320)	2289 (1273–2708)

Scenario	CO_2e concentrations	Temperature change	Probability of exceeding 2 °C
	(2100)	(max)	(max)
	ppm	°C	%
Baseline	1153 (1093–1459)	4.4 (4.1–5.3)[3.3–6.9]	100 (100–100)
RefPol	855 (788–938)	3.5 (3.2–3.8)[2.5–4.8]	99 (97–100)
550P-EU	591 (559–639)	2.4 (2.2–2.6)[1.8–3.3]	76 (68–87)
550	573 (546–630)	2.3 (2.2–2.8)[1.7–3.5]	73 (63–93)
CF450P-EU	536 (516–547)	2.2 (2.0–2.6)[1.6–3.2]	64 (50–87)
450P-EU	529 (509–569)	2.1 (2.0–2.5)[1.6–3.1]	60 (46–84)
450P-CE	519 (493–531)	2.1 (1.8–2.5)[1.5–3.1]	55 (35–84)
450	489 (469–532)	1.9 (1.7–2.5)[1.4–3.1]	36 (21–84)

2100 relative to preindustrial ranges from values of 4.1–5.3 °C in the baseline to 3.2–3.8 °C in the reference policy to 2.1–2.7 °C and 1.7–2.2 °C in the 550 ppm and 450 ppm CO_2e scenarios, respectively. For the 550 and 450 ppm CO_2e scenarios, this range of warming by 2100 is generally lower than the maximum values over the 21st century shown in Table 3. As shown in Fig. 2 (Panel a), the extent of the peak and decline behavior of temperature is model-dependent. The GCAM model shows the largest overshoot because even in the immediate action cases, it mitigates little in the near term due to the large-scale deployment of bio-CCS in the longer term [61]. Year 2100 median warming is at or below 2 degrees in the 450 ppm CO_2e case for all models except GCAM. Due to the inertia in the climate system, the degree of overshoot is significantly larger in radiative forcing than in temperature (Fig. S1 SOM). In addition, the overshoot in the 450 ppm CO_2e cases is much more pronounced than in the 550 ppm CO_2e cases owing to a stronger reduction of GHG emissions in the 2nd half of the century, including the more extensive use of negative emissions technologies.

Due to the scenario design, which defines the long-term targets in terms of cumulative CO_2 emissions, the realized long-term forcing under a given target can differ between the models. It depends on concurrent reductions of non-CO_2 gases, the assumed development of aerosol emissions (in particular sulfur) and the degree of overshoot. As can be seen from Fig. S1, there is considerable spread between forcing outcomes, but they all are above the nominal 450 ppm CO_2e (= 2.6 W/m2) target level to different degrees.[4] This translates to temperature outcomes, with three models (GCAM, MESSAGE, and REMIND) showing a less than likely chance to stay below the 2 °C target.

Compared to the 450 ppm immediate action case, staged accession leads to higher temperature outcomes in the range of 0.2–0.4 °C (450P-EU; Fig. 2, Panel b). The difference is decreased by 0.05–0.15 °C if the front runner coalition is large enough to cover a significant share of global emissions in the early period (the case of EU + China; 450P-CE). By contrast, models disagree on whether or not the fact of moderate climate action in the rest of the world makes a difference (CF450P-EU vs. 450P-EU). The MERGE-ETL model projects a significant benefit from such moderate action because it finds a large amount of carbon leakage to the rest of the world in the absence of such action (cf. Fig. 8). Thus, the importance of moderate action in the rest of the world hinges on whether or not it is needed to prevent significant carbon leakage in the initial period of fragmented action.

Despite those variations, temperature outcomes for staged accession to a 450 ppm carbon pricing regime remain

---

[4] As explained in the methodology section, the climate outcomes of the scenarios were calculated with the climate model MAGICC6.6. MAGGIC6.6 shows a slightly higher emissions-to-forcing response than most of the original climate modules of the participating models. Forcing from MAGICC6.6 is thus, on average, slightly above the indigenous forcings that were calculated by the participating models.

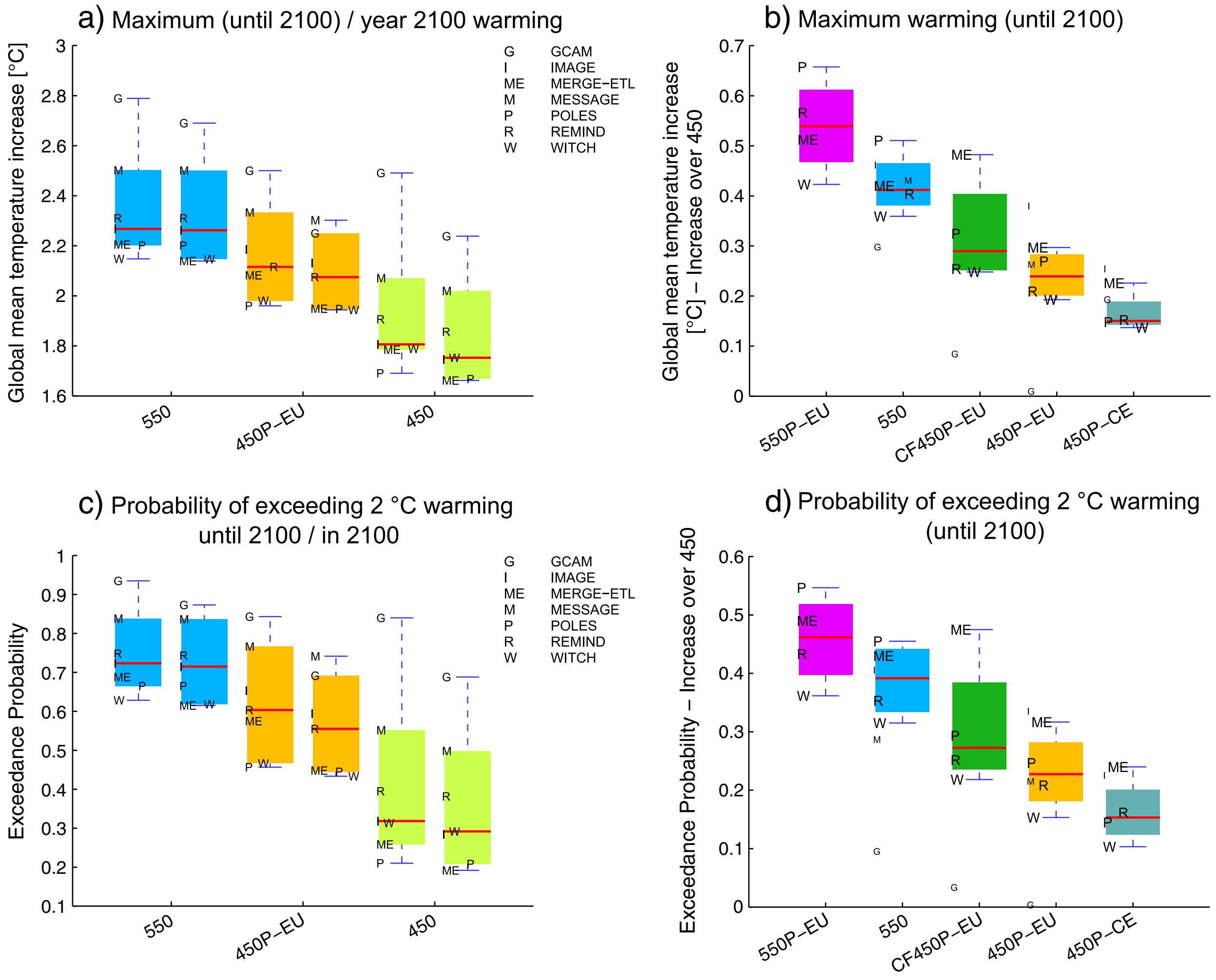


Fig. 2. Global mean warming (Panels a & b) and probability of exceeding two degrees (Panels c & d) from the staged accession and 450, 550 ppm CO_2e benchmark scenarios. The right panels (b & d) show the increase in warming/exceedance probability relative to the 450 ppm CO_2e benchmark. In the left panels (a & c), left bars for a given scenario depict the maximum temperature/exceedance probability until 2100, right bars the temperature/exceedance probability in the year 2100. Climate response is only shown for models that ran out to 2100 and captured the suite of Kyoto gases. To account for sampling bias, boxplots in the right panels only refer to the subset of models (large letters) that calculated all staged accession scenarios. Results from other models are added in small letters.

below the 550 ppm immediate action scenario. In addition, temperature is declining by the end of the century so that ambitious long-term targets may still be realized in the 22nd century. However, the degree of overshoot both in forcing and to a lesser degree in temperature increases with staged accession as a direct result of excess emissions prior to 2050 [35]. The increase in overshoot is more significant in the 450P than 550P staged accession case, adding to the already larger overshoot in the 450 ppm immediate action case compared to the 550 ppm case.

An often-used indicator for the consistency of climate outcomes with the 2 °C target is the probability of exceeding 2 °C during the 21st century [29]. This indicator is particularly sensitive to the extent of overshoot on the order of tenths of degrees, and therefore amplifies the results discussed above (Fig. 2, Panels c & d). While the exceedance probability ranges between 20 and 50% for 450 ppm immediate action (with the exception of GCAM, which depicts a strong overshoot), this probability is increased to 40–75% by staged accession. The inclusion of China in the front runner coalition has a noticeable impact on the probability due to smaller excess emissions before 2050 and smaller overshoot (a reduction of exceedance probability of 5–10% compared to the EU only case).

4.3. Mitigation costs

Emission reductions come at a cost in most models. In general, we expect global direct mitigation costs to rise with mitigation stringency. However, costs will also rise with deviations from the idealized immediate action case, in which emissions are reduced when and where they have

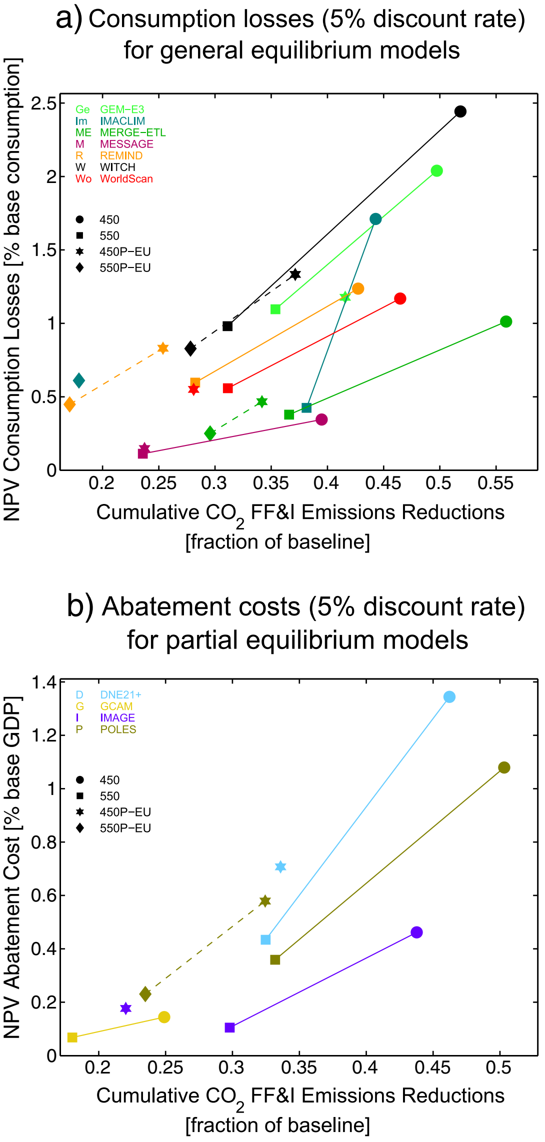


Fig. 3. Global policy costs for the period 2010–2050 as a function of cumulative CO_2 FF&I emission reductions across policy scenarios. Shown are net present values (5% discounting) of consumption losses (for general equilibrium models GEM-E3, IMACLIM, MERGE-ETL, MESSAGE, REMIND, WITCH, and WorldScan; Panel a) or abatement costs (for partial equilibrium models DNE21+, GCAM, IMAGE, and POLES; Panel b). Solid lines connect the immediate action 450 and 550 ppm cases and dashed lines the staged accessions scenarios with 450 and 550 ppm pricing for a given model. See Fig. S2 in the SOM for the results for the period 2010–2100 and the effect of the choice of discount rate.

lowest marginal abatement costs. Thus, we expect staged accession scenarios to have higher costs than immediate action scenarios for the same level of mitigation stringency. Fig. 3 brings together these two dimensions by plotting global net present value mitigation costs, aggregated over the period 2010–2050, against cumulative emission reductions, both for the 450 and 550 immediate action cases and the 450P-EU and 550P-EU staged accession scenarios (the 550P-EU was not calculated by all models). Reported values are direct (or gross) mitigation costs that do not include the direct benefits from avoided climate damages, or any co-benefits and adverse side-effects from mitigation action.

It can be seen that mitigation costs rise between 550 and 450, and between 550P-EU and 450P-EU. There are significant differences between models in terms of both the levels of costs and the cost increase between 450 and 550 ppm. This can be closely linked to the responsiveness of models to carbon pricing (Table 2) and, for general equilibrium models, to the magnitude of the economic impact they project from higher energy prices [39]. In addition, cost metrics differ across models. While we deduced consumption losses relative to the no-policy baseline from general equilibrium models (Fig. 3a), we calculate total abatement costs in terms of the area under the marginal abatement cost curve or additional energy system costs from partial equilibrium models (Fig. 3b). Both costs were aggregated in terms of net present value using a discount rate of 5%, which is in the middle range of values used in the models.[5] It should be noted that cost numbers are sensitive to the choice of discount rate, and the SOM explores the impact of different choices within the range of assumptions made in the models (Fig. S2 SOM). Despite all these differences, the level of costs and the increase between 450 and 550 ppm appear closely correlated, so that there is more agreement between models on the relative increase between the two targets (a factor of 1.5 to 3.5).

The staged accession scenarios generally have lower costs than their immediate action counterparts, but they also lead to lower emission reductions. The efficiency losses from staged accession can be identified by comparing the two lines connecting 450 and 550, and 450P-EU and 550P-EU. For the period 2010–50, some models indeed show higher costs at comparable levels of abatement effort for the staged accession scenarios, but the cost differences are rather limited. Thus, from an intertemporally aggregated and global perspective, efficiency losses from staged accession appear small. An important factor for this result is the assumption that uniform global carbon pricing, i.e. full efficiency, is obtained as of 2050 in the staged accession scenarios. However, staged accession scenarios can have a faster rise in costs during the 2030–2050 period when carbon prices rise more rapidly in the rest of the world than in the immediate action cases. This important finding of a trade-off between lower short term costs and more steeply rising costs at a later point in time is discussed in greater detail on the regional level in Section 5.

4.4. Comparing warming reductions and mitigation costs

A global assessment of staged accession has to contrast the benefits in terms of avoided climate change and the mitigation costs relative to the reference case of fragmented and moderate climate action over the 21st century. Fig. 4 provides such an

---

[5] The discount rate depends on the interest rate of capital in the models. Most models participating in the study used an internal discount rate in the range of 3–8% per year, with many models choosing a value of 5% per year. The choice of discount rate can vary over time and sectors in some models.

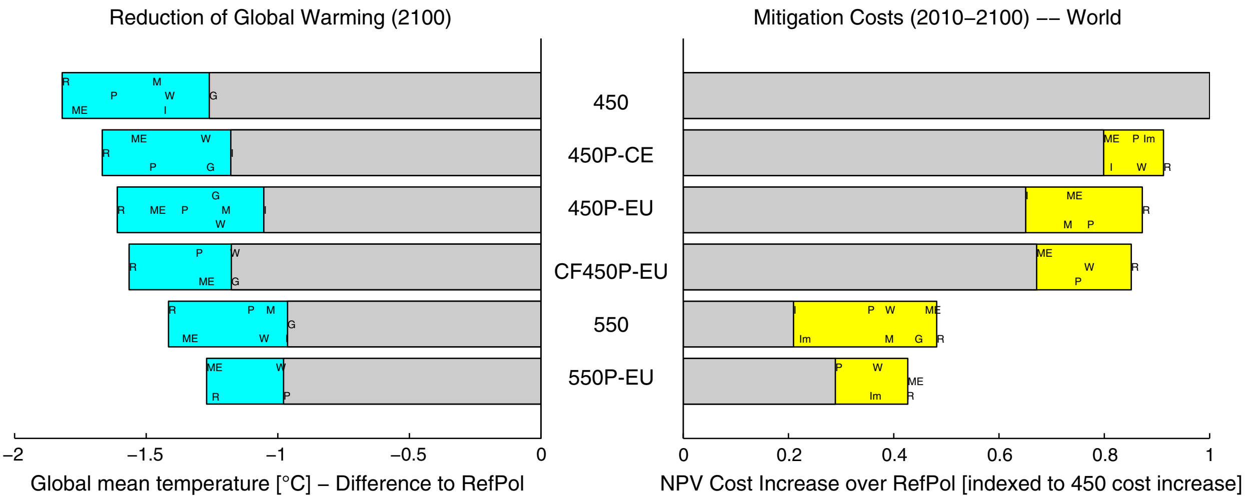


Fig. 4. Reduction in year 2100 temperature (left side) and increase in global mitigation costs (right side) over the reference policy case (indexed to the cost increase for the 450 ppm immediate action) for the various staged accession and immediate action scenarios. Mitigation costs are calculated as NPV consumption losses (GE models) and NPV abatement costs (PE models), respectively, for the period 2010–2100, discounted at 5%. Model ranges are highlighted by a change in color from the grey base of the bars. Only models with time horizon until 2100 are included. Model samples differ across scenarios and whether costs or temperature reductions are reported.

overview. Aggregated global mitigation costs and temperature reductions beyond the RefPol scenario increase with mitigation stringency. The biggest jump in temperature benefits – a reduction of warming in the year 2100 by at least 1 degree – comes from taking up ambitious climate action with global participation, independent of the choice of 450 or 550 ppm CO_2e, and immediate or staged accession. A further 0.3 to 0.5 °C in reduced warming are gained by raising the ambition level from 550 to 450 ppm CO_2e. This can be critical if climate impacts increase strongly in the 2 to 2.5 degree range. Staged accession to a stringent carbon price path that would be required for reaching 450 ppm CO_2e if all countries acted today can still deliver considerable climate benefits — approximately midways between the 550 and 450 ppm CO_2e immediate action cases. In the 450P-EU scenario, global warming is reduced by 2.1–3.3 °C compared to a situation without climate policy and by 1.1–1.7 °C compared to the reference policy. On the mitigation cost side, the largest difference is between the choice of 450 or 550 ppm CO_2e, independent of immediate action or staged accession, owing to the non-linear increase of mitigation costs with mitigation stringency. With the exception of IMACLIM and IMAGE, the additional costs over RefPol are projected to increase by a factor of 2 to 3 when moving from 550 ppm to 450 ppm CO_2e. Staged accession to 450 ppm carbon pricing leads to cost reductions of 10–35% from a global net present value perspective. However, as pointed out above and further discussed in the next section, staged accession can have higher transitional cost increases despite its lower mitigation stringency.

5. Regional perspectives on staged accession

This section explores the regional implications of staged accession and failure scenarios in greater detail. We investigate two main questions: what are the costs for front runner regions when embarking on stringent early climate action? And what are the trade-offs for latecomer regions that delay accession to a global climate regime? The section focuses on a regional breakdown between the front runner regions (Europe, and in one scenario also China) and the Rest of World (ROW). It should be kept in mind that models differ somewhat in their native region definition of the EU and China (see Section 2 and SOM). Despite these limitations, a comparison of mitigation costs and emissions in front runner vs. ROW regions is feasible.

5.1. Regional mitigation costs in reference and benchmark scenarios

Regional mitigation costs in the immediate action scenarios are considerably higher in the second half of the century than in the first due to the cumulative impact of mitigation policy (Figs. 5 and S3). However, this needs to be put into the context of the assumption of a 12-fold increase of gross world product in purchasing power parity between 2005 and 2100 that was adopted by all models for the baseline case (SOM). As a consequence of this rise in mitigation costs, models estimate significantly higher long run costs for immediate action on the 450 ppm CO_2e target than for weak action in the reference policy case. For the nearer-term mitigation costs until 2050, this is still true for ROW, while the picture for the EU is mixed. A few models show similar costs in the reference policy than for immediate action for the period 2010–50, indicating among other things, inefficiencies from implementing domestic EU emission reductions in combination with technology targets in these model setups.[6]

---

[6] Cost estimates of reaching national emissions targets for the year 2020 are sensitive to assumptions about short-term economic growth. The harmonized GDP assumptions used in this study account for the effect of the financial crisis 2008–10 but did not anticipate the ensuing economic crisis in the Eurozone. The assumed output of EU27 in 2020 is about 5% higher compared to current economic growth forecasts from the IMF ([62]; see Section S3.4 in SOM).

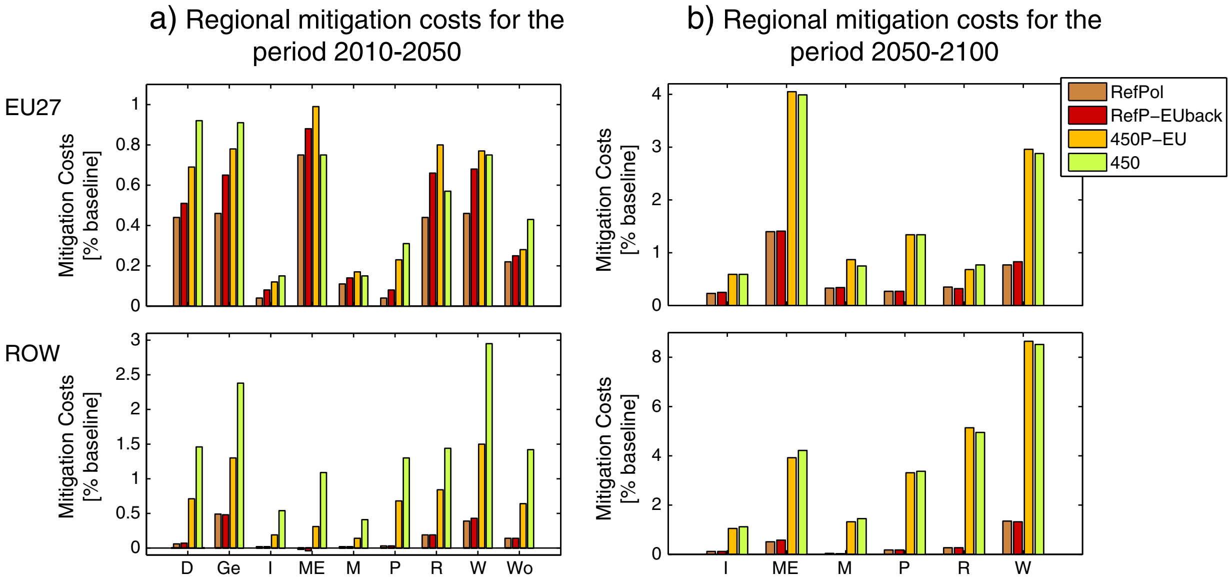


Fig. 5. Regional mitigation costs for (a) the period 2010–2050 and (b) 2050–2100. Shown are net present value consumption losses (discounted at 5%; relative to baseline consumption) for general equilibrium models (Ge = GEM-E3, Me = MERGE-ETL, M = Message, R = ReMIND, W = WITCH, and Wo = WorldScan) and abatement costs (relative to baseline GDP) for partial equilibrium models (I = IMAGE, D = DNE21+, P = POLES). The figure includes only those models that report mitigation costs for the staged accession and reconsideration scenarios with the EU as front runner (450P-EU and RefP-EUback). ROW includes China.

While reference policy costs for ROW are lower or of similar magnitude as for the EU, they are higher in the case of immediate action by a factor 1.5 to 5.5. Higher than average mitigation costs in the developing world have been identified in other studies before, e.g. [63]. Among other things, this is due to higher carbon intensity and larger emission reductions from a strongly rising baseline in these countries. It is important to note, however, that these are cost estimates in the absence of burden sharing mechanisms where, for instance, countries with below-average mitigation effort would compensate other countries with larger effort [64]. The effect of burden sharing schemes on net mitigation costs has been studied in other model comparison exercises [27,63] but was not a subject of this study. Apparently, burden sharing mechanisms will be needed in the medium to long run to establish political acceptability for a global cooperative solution that utilizes the least costly mitigation potentials at the margin independently of where it occurs.

5.2. The stakes of front runner action faced by the European Union

The impact on mitigation costs of the EU acting as front runner can be measured against the costs in the reference and immediate action scenarios, which epitomize the boundary cases of no front runner and everybody being a front runner. As shown in Fig. 5, the long run costs (2050–2100) of the EU for leading the way to a global 450 ppm pricing regime (450P-EU) are very similar to its immediate action costs. Until 2050, models vary in their estimate whether staged accession would be more or less costly for the EU compared to immediate action. This depends on whether or not they see unilateral roadmap action until 2030 followed by a gradual transition to 450 ppm carbon pricing as more stringent than the 450 ppm immediate action which would allow the EU to fully benefit from emission reductions elsewhere.

In the reconsideration scenario (RefP-EUback), the EU transitions back to its reference policy after 2030 when recognizing that the rest of the world will not adopt more ambitious climate action. Models disagree about the cost mark-up due to front runner action in the period 2010–2050. Those that see the roadmap action in 450P-EU as similarly costly or more costly than immediate action until 2050 also show significant cost mark-ups due to failure in RefP-EUback compared to the reference policy. If inefficiencies in front runner action are significant, sunk costs due to failure are obviously also significant.

For the EU, other economic considerations may play an equally important role for the evaluation of whether or not the EU should act as a front runner on ambitious climate action. Such considerations may include energy security, trade and competitiveness, as well as external environmental and health costs unrelated to climate change. [32] takes a closer look at potential co-benefits for the case of Europe unilaterally adopting stringent climate action in the form of the EU climate and energy roadmap. A robust result from all models is that climate action in Europe leads to higher energy efficiency, higher utilization of renewable energy, and a diversification in the supply of energy, thereby reducing its dependence on fossil fuel imports and improving energy security. These findings hold regardless of whether Europe is able to inspire the rest of the world to join its mitigation effort or not. The higher overall utilization of low-carbon technologies in turn reduces the environmental and health costs of electricity production, mainly due to a reduction of coal use without CCS in favor of non-biomass renewables.

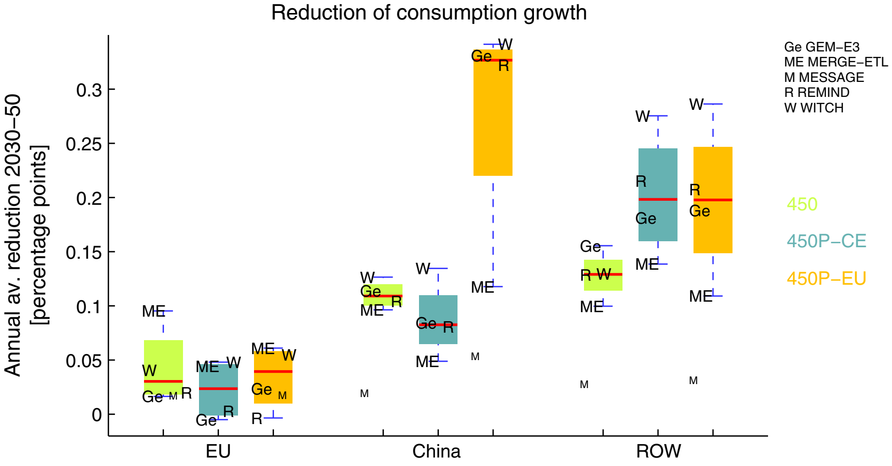


Fig. 6. Reduction in global consumption growth over the period 2030–2050 relative to the no policy baseline (for general equilibrium models GEM-E3, MERGE-ETL, MESSAGE, REMIND,[7] and WITCH). Shown are annual average growth rate reductions in percentage points for the 450 immediate action and staged accession scenarios and for three world regions, EU, China and ROW (excluding China). To account for sampling bias, boxplots only refer to the subset of models (large letters) that calculated all three scenarios. MESSAGE results are added in small letters. Results of the other two general equilibrium models are not included, because WorldScan did not disaggregate the China + ROW region, and the transient behavior of consumption losses in IMACLIM is heavily influenced by the addition of infrastructure policies in the climate policy scenarios. IMACLIM does not show a significant variation of consumption growth rates between immediate action and staged accession scenarios.

These cost savings from reduced non-climate externalities due to implementing the EU roadmap may offset a large portion of the climate policy costs.

5.3. Trade-offs of early and delayed action for China

China is the world's largest emitter with a rapidly growing economy and a heavily coal-based energy system. This makes it a key player in the quest for achieving long-term climate targets. It also affects the trade-offs China faces between the choice of joining the global mitigation effort immediately or delaying accession to a global climate regime. The reference policy costs for China are projected to be low (see Fig. S3 in SOM) as most models see the carbon intensity target for 2020 being realized by the adoption of the technology policies without additional need for carbon pricing (see Fig. 1). By contrast, immediate action costs are higher than the world average owing to the large mitigation effort that China will have to undertake in such a scenario. Delaying the adoption of 450 ppm carbon pricing until after 2030 (450P-EU) can lead to cost reductions by a factor of 1.7 to 5.2 over the period 2010–2050 based on the ensemble of models that reported this scenario (at 5% discounting of future costs), while long run costs after 2050 are largely unaffected (Fig. S3).

However, all models show a steeper increase in mitigation costs for delayed action (450P-EU) than immediate action (450) during the 2030–50 transition phase in which the carbon price is ramped up to 450 ppm pricing levels. A rapid rise in mitigation costs can bring a number of socio-economic and institutional challenges. The resulting impact on consumption growth rates as estimated by the general equilibrium models can provide a useful proxy for the magnitude of these challenges [4,65], although the modeling results alone will not be able to capture them fully. Fig. 6 shows the reduction of consumption growth in China for the period from 2030 to 2050 across the immediate action and staged accession scenarios. Growth rate reductions relative to the baseline range up to an annual average of 0.33 percentage points in the 450P-EU scenario where China transitions to a global climate regime only after 2030 as compared to 0.13 percentage points in the immediate action case. The projected growth rate reductions can be compared with estimated slowdowns of consumption and GDP growth in the past and present. For example, the World Economic Outlook [62] projects EU27 output to grow by only 6.5% over the period 2008–2017 due to the financial and Euro crises, and return to post-crisis growth rates of 2% per year thereafter. Assuming that in the absence of these crises output in the EU would have grown at a steady 2% per year. Europe is currently suffering an annual average 1.4 percentage point reduction of GDP growth over the decade 2008–2017. This is an order of magnitude larger than the reduction of global consumption growth from climate policy, as projected in this study.

If China chooses to take up front runner action together with the EU, and others follow onto the path to 450 ppm carbon pricing after 2030 (450P-CE), its mitigation costs will be comparable to, or in some models (MERGE-ETL, WITCH) even higher than in the immediate global action case over the period 2010–2050 (Fig. S3). The higher costs accrue mostly in the near term due to balance of trade effects and larger mitigation efforts assisted by higher

---

[7] REMIND includes an intertemporal capital market which allows regions to temporarily adjust their current account position within the constraints that every region needs to balance its current account at the end of the time horizon, and that current account surpluses and deficits need to be balanced across regions at each point in time. Consumption growth rate reductions reported for REMIND include changes in the current account position to cancel out temporary transfers between consumption and current account in response to climate policy [66].

fossil fuel prices than in the immediate action case. The temporal profile of mitigation costs shifts forward compared to the delayed action (450P-EU) scenarios with a faster increase before 2030, and a consequently slower increase in the period 2030–50.

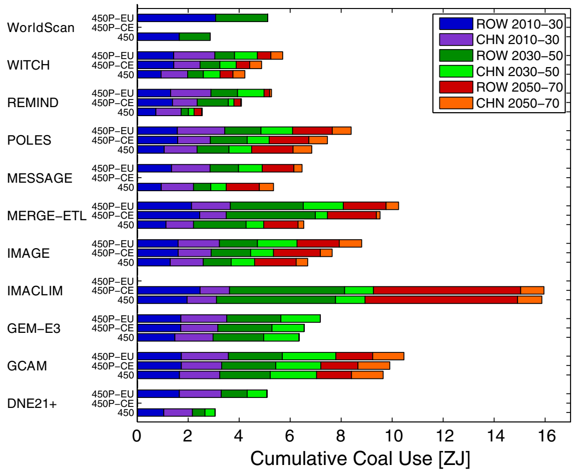
The costs of reconsideration (RefP-CEback) would be significant in the 2010–2050 period, where they are higher than for delayed accession (450P-EU). Since China's climate action in the reference policy is assumed to be very moderate, a failed attempt to nudge the world into global cooperative action would imply a considerable amount of sunk costs due to front runner action up to 2030. Thus, the stakes of front runner action are higher for China than for the EU. However, this critically hinges on the assumption of the level of ambition in the reference policy. If China chooses to embark on more ambitious climate action domestically than was assumed in this study, going a step further to commit to international leadership will pose less of a challenge. In addition, as for the EU, direct mitigation costs will not be the only consideration for China when evaluating its level of climate policy commitment. Given the significant air pollution and energy security problems that are caused by China's reliance on fossil fuels and coal in particular, a reduction of coal use without CCS, which has to be one of the cornerstones of any effective climate policy, can bring large co-benefits [15,16].

5.4. Trade-offs of delayed action for the rest of the world

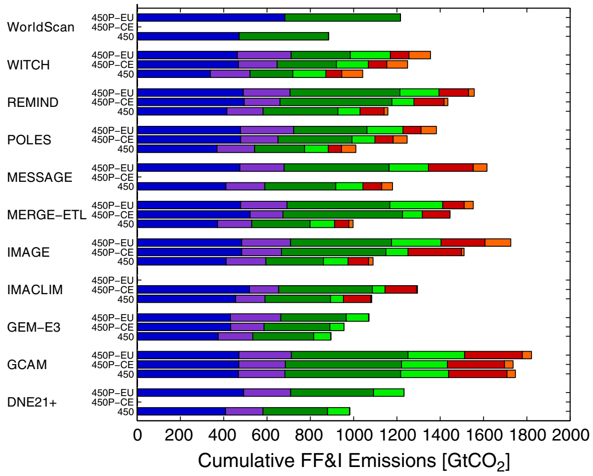
The comparison between immediate (450) and delayed accession (450P-EU) to a global climate regime shows a trade-off between higher short-term mitigation costs and higher transitional medium-term mitigation challenges for the rest of the world, including China if it foregoes front runner action. Until 2050, ROW has clear benefits in terms of lower costs from delaying 450 ppm carbon pricing until after 2030 (a factor of 1.7 to 3.6 lower costs in 450P-EU compared to immediate action), while long term mitigation costs after 2050 are of comparable magnitude.

The trade-off of delayed action consists in larger transitional mitigation challenges in the medium term. First, mitigation costs are projected to rise more rapidly in the transition period 2030–2050, as shown by a larger reduction in consumption growth rates over this period in the 450P-EU compared to the 450 scenario (Fig. 6). Second, delayed action can result in a stronger carbon lock-in in

a) Cumulative coal use during 2010-2070



b) Cumulative FF&I CO_2 emissions during 2010-2070



c) Cumulative carbon tax expenditure over 2010-2070 (undiscounted)

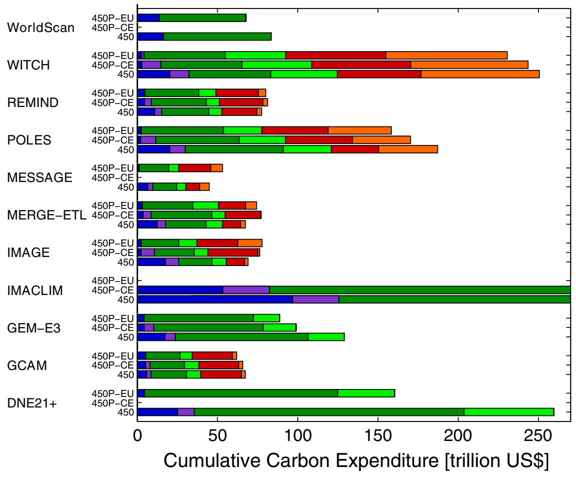


Fig. 7. Comparison of cumulative coal use (Panel a), fossil fuel and industry CO_2 emissions (Panel b) and carbon price expenditures (Panel c) in world regions outside of the EU between the immediate action (450) and staged accession scenarios (450P-EU, 450P-CE). Fossil fuel CO_2 emissions after 2070 turn negative in many models and are not included in this figure. WorldScan, GEM-E3 und DNE21+ have a time horizon until 2050. WorldScan does not report separate numbers for China, thus its values for ROW constitute the sum over China and all other regions outside the EU. Carbon price expenditures in IMACLIM reach 626 trillion (450) and 650 trillion USD (450P-CE) until 2070 (405 and 401 trillion USD, respectively, until 2050; sum over ROW and China). For comparison, the undiscounted GDP over the period 2010–2070 is assumed to be around 7000 trillion USD in China plus ROW in this study.

ROW that persists into the 2nd half of the century. The long lifetime of fossil-based energy infrastructure creates significant inertia that prevents rapid decarbonization unless power plants are retired prematurely, left idle or retrofitted with CCS [67]. Also, alternative low-carbon technologies require time to diffuse into the system and ramp up to significant scale [68]. As a result, the carbon intensity of energy production may respond only slowly to carbon prices or other policy or market signals. As can be seen in Fig. 7, delayed accession leads to higher coal use (Panel a) and fossil fuel emissions (Panel b) in ROW not only during the initial period of low carbon prices, but also during 2030–50 where ROW transitions to 450 ppm carbon pricing, and after 2050 when carbon prices in staged accession and immediate action cases are identical (see also [33]). In fact, only the smaller part of excess emissions over the immediate action case stems from the initial period until 2030, while the larger part (40% to 80% depending on the model) accrues thereafter. The carbon lock-in is significantly increased if China delays the adoption of stringent carbon pricing together with the rest of the world.

As carbon prices rise steeply to 450 ppm levels after 2030 in ROW, so does the carbon price expenditure, i.e. the amount paid for residual emissions (= carbon prices times emissions). As can be seen from Fig. 7c, the magnitude of carbon price expenditures in ROW and China is large in all climate policy scenarios, with the largest part occurring after 2030 (in undiscounted terms). Most models project that the 2030–70 carbon price expenditure in ROW and China is further increased by the carbon lock-in from delayed action (by −2 to 32 trillion USD, or −4% to 74%, for 2030–2070 between 450P-EU and 450). While the models do not show significantly higher long term mitigation costs due to the larger carbon tax expenditures in the staged accession scenarios (Figs. 5, S3), there can be distributional implications that are usually not well captured by the type of models used in this study. Since expenditures accrue as revenues to the state or the holders of emissions allowances, a larger carbon price expenditure can increase institutional challenges to allocate or recycle the revenues (who benefits?). If the allocation problem is not solved efficiently, this can translate into higher long-run mitigation costs from delayed action even if excess emissions in an early period do not have to be compensated for.

6. Carbon leakage and technology spillovers due to front runner action

An important concern about unilateral climate action is carbon leakage. Carbon leakage would induce excess emissions in non-acting countries and thus would reduce the environmental effectiveness of the climate policy. In principle, carbon leakage can occur in any climate policy regime with regionally fragmented carbon pricing, such as the reference policy scenario, but its magnitude is expected to increase with the carbon price differentials between regions. Thus, stringent carbon pricing in a front runner region as considered here may be particularly prone to carbon leakage effects. This section investigates the driving and counteracting mechanisms of carbon leakage as well as the projected amount of leakage in a staged accession climate policy setting.

The analysis focuses on the near-term period until 2030 and is restricted to the various carbon leakage channels that are represented in the participating models (see Table S3 in SOM). All models represent carbon leakage via the energy market channel, through which reduced demand for fossil energy in front runner regions lowers international fossil fuel prices, inducing higher fossil fuel consumption in other regions. Related to this is the industry or competitiveness channel, through which higher energy prices in front runner regions induce energy-intensive industries to re-locate to regions with lower energy prices and weaker or no abatement policies. This channel is represented in the multi-sectoral CGE models participating in the study (GEM-E3, IMACLIM, WorldScan). Some studies [69,31][8] argue that the competitiveness channel dominates whereas others [70,71][9] identify the energy channel as the major driver of carbon leakage.

Carbon leakage can also be triggered by indirect land-use change emissions if the front runner regions substitute fossil fuels with bio-fuels that are imported from non-abating regions. This effect is captured by integrated assessment models that include a dynamic land-use model such as GCAM and IMAGE. Finally, early mitigation action can also accelerate the advancement of low-carbon technologies and thus spill over to other regions that adopt these technologies as well. This counteracting mechanism to carbon leakage is represented by models that include endogenous technology learning and technology spillovers in this study such as IMACLIM, MERGE-ETL, POLES, REMIND and WITCH. The varying representation of leakage channels across models needs to be kept in mind for the cross-model comparison below. Where appropriate, we report results from individual models that investigated specific leakage channels in greater detail.

6.1. Fossil fuel and industry emissions leakage

The aggregate effect of carbon leakage through the energy and competitiveness channels and technology diffusion in the period of fragmented action until 2030 is described in Fig. 8. Fig. 8a shows the results for Europe following the EU Roadmap, i.e. approx. 35–45% emission reductions by 2030 relative to 1990 depending on the model implementation. We distinguish two different levels of climate action in the rest of the world: reference climate policy (RefPol; squares) and no climate policy (Base; circles). Obviously, the EU Roadmap leads to stronger emission reductions relative to the no-policy baseline than to the reference policy case, which already accounts for approx. 30% emission reductions by 2030 relative to 1990. Different baseline emission trends in the absence of climate policy lead to a large range of emission reductions in the EU across models (MERGE-ETL has a very carbon-intensive baseline, and IMACLIM and GCAM include Turkey in their EU model region).

---

[8] [31] summarizes the results of the EMF29 model comparison study on carbon leakage.

[9] [71] is based on a single-model framework.

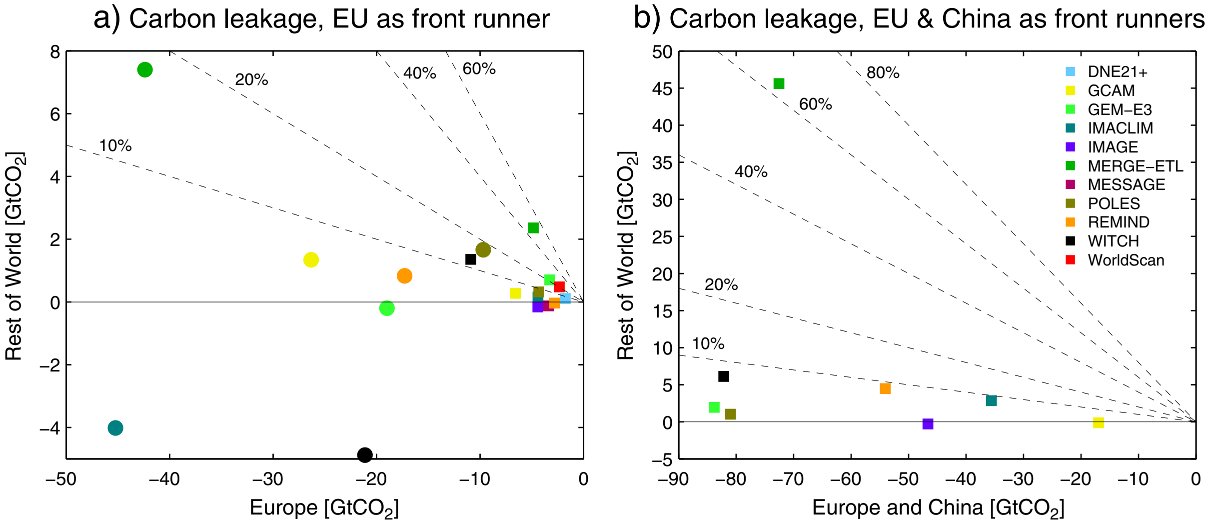


Fig. 8. Cumulative changes in fossil fuel and industry emissions for the period 2010–2030 in the front runner regions (EU: Panel a and EU + China: Panel b) plotted against changes in cumulative emissions in the rest of the world. Panel a shows the differences between the CF450P-EU and Base scenarios (circles) and between the 450P-EU and RefPol scenarios (squares). Panel b shows the differences between the 450P-CE and RefPol scenarios. Dashed lines connect points of equal leakage rates ranging from 10% to 80%.

The emission changes in non-abating regions are mixed. Some models derive increasing emissions whereas others project emission reductions. The absolute change of emissions is smaller when the rest of the world already follows moderate climate policy, but carbon leakage rates relative to EU emission reductions are comparable. Three models, MERGE-ETL (leakage rate: 49%), GEM-E3 (22%) and WorldScan (21%), show significant carbon leakage rates against the reference policy case. The large carbon leakage in MERGE-ETL is due to higher coal and oil use in the rest of the world induced by lower fossil fuel prices in combination with higher uranium demand for nuclear power in the EU. The results in GEM-E3 and WorldScan reflect carbon leakage via the competitiveness channel. [37] explores the carbon leakage effect in GEM-E3 in greater detail. The economy-wide 22% carbon leakage rate is comprised of different sectoral leakage rates. The highest sectoral leakage is found in the energy conversion sector and energy-intensive industries. Among industries, metal production and the chemicals sector are found to have the highest leakage rates. These sectors are characterized by both high energy intensity and high trade exposure.

Only a subset of models investigated the case where the rest of the world follows no climate policy at all (indicated by the circles in Fig. 8a). Again, MERGE-ETL shows the highest carbon leakage, but the leakage rate relative to the EU emission reductions, now measured against the no policy baseline, is smaller (17%). Two models, WITCH (leakage rate: −23%) and IMACLIM (−9%), show significant negative carbon leakage. This is due to technology diffusion effects. In particular in WITCH, the increased deployment of EU wind power capacity triggers a decrease in wind power costs that diffuses to the rest of the world; this in turn crowds out some of the coal power investments within all regions.

Fig. 8b shows the results for the case that Europe and China adopt the carbon price of the 450 scenario compared with the reference policy case. The main difference is that the combined emission reduction is much stronger than if Europe acts alone. Moreover, while the absolute amount of carbon leakage to other regions is larger, its magnitude relative to the strong reductions in Europe and China is found to be smaller in the majority of models. For example, [37] found that the leakage rate in GEM-E3 drops from 22% to 2% in cumulative terms when China joins the GHG mitigation action because of the increased coalition size and because shifts of production away from China's highly carbon-intensive industry may in part be to regions with lower carbon intensities. Only MERGE-ETL shows strong positive carbon leakage with the leakage rate increasing to 63%, partly because increased use of uranium by the EU and China induces the rest of the world to substitute coal for nuclear power.

Since most models participating in this study comprise a detailed representation of the energy sector, carbon leakage via the energy channel can be traced back to re-allocations on the international markets for coal, oil, and gas. [33] provides a comparative analysis of energy market leakage across all models, and [36] performs an in-depth analysis with REMIND. The studies show that the strength of fossil fuel leakage differs for coal, oil and gas and across models. Generally, oil and gas leakage is stronger than coal leakage because coal trade is relatively small. The general pattern, however, is one of limited carbon leakage through the fossil fuel market channel. In several models, the story is even one of negative carbon leakage as the rest of the world replaces coal with gas due to reduced demand for gas among the early movers.

6.2. Technology diffusion

Increased demand for low-carbon technologies in mitigating regions can lead to technology learning that in turn may induce diffusion of such technologies to other regions. In the reference policy scenario, models show that the regionally fragmented policy targets indeed promote technology innovation [72]. When there are front runner regions that undertake yet more stringent mitigation action, their energy sectors are further transformed toward the use of low-carbon technologies. However, most of the models show that outside of the front runner coalition, technology deployment in the electricity sector is not significantly affected and continues to be determined by the technology and climate policy objectives in the reference policy. Exceptions exist in the case of an EU–China coalition, in which the POLES and IMACLIM models indicate that CCS becomes a sufficiently prominent option in the front runner regions to induce a learning effect and technology spillovers [34]. Other models generally show less technology spillover effects. MERGE-ETL, for example, suggests nuclear (considered a mature technology) as a prominent decarbonization option for an EU–China coalition, hence technology diffusion impacts on the rest of the world are small, and are overwhelmed by carbon leakage effects if limited access to uranium induces the rest of the world to replace nuclear energy with coal. Regarding wind energy technologies, most of the models show that the reference policy case already brings about significant technology learning and high levels of deployment. Given that most models suggest only limited technology responses to front runner action from the other regions that continue with their reference policies, technology diffusion might require dedicated policy instruments.

6.3. Land-use emissions leakage

One modeling team (IMAGE) also looked into the potential consequences of a land-use channel of carbon leakage [38]. If single regions like the EU and China move ahead, they import bioenergy from international markets to reduce coal, oil, and natural gas consumption. Higher bioenergy supply is likely to lead to higher emissions from land-use change (compared to baseline), which leads to an increase in land-use emissions. [38] finds that pursuing early action by the EU alone and EU and China together may somewhat increase land use emissions until 2050. The prominence of the bio-energy channel differs between scenarios because the amount of land use emissions, as a result of increased bio-energy production, varies between regions from which bioenergy is imported. This highlights the sensitivity of land carbon leakage to assumptions about the regional pattern of bioenergy production. More research is needed to better understand the land carbon dynamics in fragmented policy scenarios.

7. Conclusions

The current climate policy situation is marked by the long-term aspiration of stabilizing climate change at or below 2 °C of global warming, but also by fragmented and moderate short-term action, and by large uncertainty about future national climate policies and the prospect of an international climate agreement. A defining question for the way forward for global climate policy is how to build a bridge between short-term realities and long-term aspirations. Obviously, countries are unlikely to commit to more stringent mitigation action at the international level than what they can support at the national level. On the other hand, national climate action requires international reciprocity for reasons of both environmental effectiveness and stabilizing the expectations of economic and public actors.

This study contributes to mapping out the climate policy landscape by exploring how staged accession can constitute such a bridge. We have investigated how effective a group of countries can be in leading the way with stringent mitigation action even if the rest of the world does not join the effort for two more decades. The analysis has focused on staged accession scenarios where a front runner coalition – the EU or the EU and China – embarks on ambitious climate action broadly consistent with the 2 degree target, and the rest of the world transitions to the global climate regime between 2030 and 2050. The study adds to earlier work on staged accession scenarios, in particular the two model comparison exercises RECIPE [25] and EMF22 [23] that looked at the achievability of long-term climate targets if a large number of countries delay the adoption of such targets. Major innovations of this study include the improved representation of the currently fragmented climate policy landscape with unprecedented detail in a model comparison framework; the broad exploration of the payoffs and tradeoffs for front runner and follower regions including transitional costs, carbon lock-ins and benefits in terms of reduced global warming; the specific investigation of the EU and China in staged accession scenarios; and an analysis of dynamic leakage effects during the initial period of fragmented action until 2030. While previous studies assumed a willingness to adopt the original target after delay, this study explores the scenario that long-term climate action would not compensate for the delay in adopting a global climate policy approach.

The following key findings emerge:

7.1. Environmental effectiveness

Initiating staged accession to an ambitious global climate policy regime can deliver significant climate mitigation even if the majority of countries join only after 2030 and the original climate target is relaxed. Concretely, if front runner countries can induce others to join a global climate regime after 2030, then global warming until 2100 is projected to be reduced by more than 1 degree compared to a reference policy case of moderate and fragmented regional action over the 21st century. While the climate benefits from staged accession are significant, the resulting climate outcome is unlikely to be consistent with a 2 degree target [35]. Phasing in 450 ppm carbon pricing outside Europe after 2030 leads to 0.2–0.4 °C higher warming compared to the 450 ppm immediate action scenario, and to a 0.15–0.35 higher probability of exceeding the 2 °C target. This is caused by higher overall emissions over the 21st century, but also by higher temperature and forcing overshoot due to the excess emissions until 2050. The addition of China to the front runner coalition can reduce the pre-2050 excess emissions by 20–30%, which lowers peak warming by 0.05–0.15 °C and the probability of exceeding 2 °C by 0.05–0.1 compared to the EU acting alone. Thus, early action in China has a measurable impact on warming outcomes. Temperature trajectories in scenarios of staged accession to 450 ppm carbon pricing show a downward temperature trend in 2100, so that warming would eventually be limited to 2 degrees if those trends were continued. If front runner action fails to nudge the rest of the world into ambitious global action, the warming benefit compared to reference policy will be negligible. Front runner action should therefore be highly concerned with setting effective examples for others to follow.

7.2. Economic efficiency

Staged accession to a global climate regime induces economic inefficiencies. In the initial period of globally fragmented action, regions may have to forego the least-cost mitigation potential at the global margin due to regional differences in greenhouse gas prices. While such price differentials can in turn lead to carbon leakage, on average we find this effect to be limited in the case of EU front runner action until 2030, with leakage rates that are comparable to [31]. However, a few models show substantial carbon leakage via coal and uranium markets [34] and uncertainty about carbon leakage effects through bioenergy markets [38,73]. Carbon leakage effects, particularly from the re-location of energy intensive industries, can be significantly reduced if China joins the front runner coalition [37].

Models find lower global mitigation costs for staged accession than for immediate action scenarios (by 10–35% compared to the 450 ppm scenario), albeit for lower levels of emission reductions. However, staged accession leads to more rapidly rising mitigation costs in the transition period between 2030 and 2050 for regions that delay climate action. The models project an additional slowing of consumption growth by up to 0.3 percentage points in these regions. Delayed action also leads to a continued build-up of fossil fuel infrastructure until 2030 that is only weakly moderated by the low carbon prices during this period. This result has also been identified in the AMPERE companion study on delayed action [40,74]. As a result of this carbon lock-in, the rest of the world continues to have higher emissions in the long run, even after 2050, when carbon prices have reached the level of the immediate action case. This in turn leads to higher carbon price expenditures in the long run, with the potential for larger challenges to institute climate policy. Thus, the rest of the world faces a clear trade-off between higher mitigation costs in the short term and larger transitional medium-term challenges with adopting stringent climate action.

7.3. Stakes faced by front runners

Front runners are faced with the risk that their additional effort may have been in vain if the rest of the world chooses not to go for ambitious climate action in the end. In the case of the EU, the stakes depend on how EU front runner action compares to the EU reference policy until 2030. Since the EU is assumed to already follow relatively stringent climate policies in the reference case, many models see the EU's stakes not rising by much if front runner action is adopted.

The stakes for front runner action by China are projected to be higher than for the EU. However, this critically hinges on the assumption of the level of ambition in the reference policy. In addition, both the EU and China will not only consider their direct mitigation costs when evaluating their level of climate policy commitment. Exploiting synergies in terms of reduced air pollution, increased energy security and reduced fossil fuel expenditures will also play a role [32]. Our findings suggest that ambitious national climate policy plans improve the case for front runner action, which highlights again the close connection between the national and international climate policy levels. They also suggest that countries considering international leadership on climate policy may look for coalition partners among those countries that show a significant willingness to pay in terms of their national climate action plans. Finally, short-term co-benefits of climate policy in the presence of multiple externalities can be a key element for tackling the challenge presented by the short-term costs of mitigation.

Several caveats of this study need to be mentioned. First, the results are contingent on the models that participated in this study. While the use of multiple models in a comparison exercise greatly improves the assessment of uncertainty due to different model assumptions and structures, it cannot capture the full range of uncertainty. Second, we have used a range of metrics to explore the benefits (maximum and 2100 global mean warming, probability of exceeding two degrees) and costs (aggregate mitigation costs, transitional costs, carbon price expenditures) of climate action. While these cover key elements of cost-benefit considerations, a full assessment of the costs and benefits of climate policy will rely on a broader set of indicators, including regional climate impacts, institutional challenges, and co-benefits and adverse side effects. Third, we approached the question of whether or not to act as a front runner on climate policy, and whether or not to wait with joining global action, in a scenario mode. While this is the adequate choice for the large scale models with detailed representations of the energy–economy system that were used for this study, complementary analysis, including game-theoretic modeling, is needed to explore the incentive structure of staged accession. Finally, a representation of the current climate policy landscape always runs the risk of being overtaken by events, as the policy environment is evolving rapidly.

Irrespective of these caveats, our study provides an important analysis of how to bridge the current climate policy situation and long term aspirations. Effective climate policy leadership can play an important role in making or breaking climate targets, if it helps to build expectations about long term climate action, to exploit synergies with other policy objectives, and to avoid extensive carbon lock-ins over the next two decades.

Acknowledgement

The research leading to these results has received funding from the European Union's Seventh Framework Programme FP7/2010 under grant agreement n° 265139 (AMPERE).

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.techfore.2013.09.021.

References

[1] IPCC, Climate change 2007: Mitigation, in: B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (Eds.), Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 2007.

[2] The World Bank, Turn Down the Heat: Why a 4 °C Warmer World Must be Avoided, The World Bank, Washington DC, United States, 2012.

[3] UNFCCC, Report of the Conference of the Parties on its Seventeenth Session, held in Durban from 28 November to 11 December 2011, In: Addendum Part Two Action Taken by the Conference of the Parties at Its Seventeenth Session, UN Framework Convention on Climate Change, 2011, (FCCC/CP/2011/9/Add.1).

[4] G. Luderer, C. Bertram, K. Calvin, E. De Cian, E. Kriegler, Implications of weak near-term climate policies on long-term climate mitigation pathways, Clim. Chang. (2014), http://dx.doi.org/10.1007/s10584-013-0899-9 (online first).

[5] G.J. Blanford, E. Kriegler, M. Tavoni, Harmonization vs. fragmentation: overview of climate policy scenarios in EMF27, Clim. Chang. (2014), http://dx.doi.org/10.1007/s10584-013-0951-9(online first).

[6] E. Moxnes, E. van der Heijden, The effect of leadership on a public bad experiment, J. Confl. Resolut. 47 (6) (2003) 773–795.

[7] W. Güth, M.-V. Levati, M. Sutter, E. van der Heijden, Leading by example with and without exclusion power in voluntary contribution experiments, J. Public Econ. 91 (5–6) (2007) 1023–1042.

[8] J. Potters, M. Sefton, L. Vesterlund, Leading-by-example and signaling in voluntary contribution games: an experimental study, Economic Theory 33 (1) (2007) 169–182.

[9] M. Jacob, K. Lessmann, Signaling in international environmental agreements: the case of early and delayed action, Int. Environ. Agreements 12 (4) (2012) 309–325.

[10] M. Jakob, C. Flachsland, Strategic Incentives for Early Movers in Sequential Climate Games. Working paper presented at the 5th Atlantic Workshop on Energy and Environmental Economics, 25/26 June 2012, A Toxa.

[11] M. Friman, B. Linnér, Technology obscuring equity: historical responsibility in UNFCCC negotiations, Clim. Pol. 8 (4) (2008) 339–354.

[12] European Union, Decision no 406/2009/EC of the European parliament and the council of 23 April 2009 on the efforts of member states to reduce their greenhouse gas emissions to meet the community's greenhouse gas emission reduction commitment up to 2020, Off. J. Eur. Union L140 (2009) 136–148.

[13] European Commission, Roadmap for moving to a competitive low carbon economy for 2050, COM 1122011. (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0112:FIN:EN:PDF, last accessed March 2013).

[14] S. Wang, Z. Zhang, Effects of climate change on water resources in China, Clim. Res. 47 (1–2) (2011) 77–82.

[15] J. Cao, M. Ho, D. Jorgenson, The co-benefits of mitigating the global greenhouse gases in China — an integrated top-down and bottom-up modeling analysis, EfD Discussion Paper 08, Beijing, China, 2008.

[16] H. Kan, R. Chen, S. Tong, Ambient air pollution, climate change, and population health in China, Environ. Int. 42 (2012) 10–19.

[17] N. Zhou, D.G. Fridley, M. McNeil, N. Zheng, J. Ke, M. Levine, Peak CO_2? China's Emissions Trajectories to 2050, China Energy Group, Lawrence Berkeley National Laboratory, 2011. (LBNL-4871E).

[18] D. Fridley, N. Zheng, N. Zhou, J. Ke, A. Hasanbeigi, B. Morrow, L. Price, China Energy and Emissions Paths to 2030, 2nd edition China Energy Group, Lawrence Berkeley National Laboratory, 2012. (LBNL-4866E).

[19] Council of the European Union, 15th EU–China Summit: Towards a Stronger EU–China Strategic Partnership, Joint Press Communiqué, 2012. (14022/12 PRESSE 388 www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/132507.pdf, last accessed March 2013).

[20] B. Fisher, N. Nakicenovic, K. Alfsen, J. Corfee Morlot, F. de la Chesnaye, J.-Ch. Hourcade, K. Jiang, M. Kainuma, E. La Rovere, A. Matysek, A. Rana, K. Riahi, R. Richels, S. Rose, D. van Vuuren, R. Warren, Issues related to mitigation in the long-term context, 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 Inter-governmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 2007.

[21] D.P. Van Vuuren, J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S. Smith, S.K. Rose, The representative concentration pathways: an overview, Clim. Chang. 109 (1–2) (2011) 5–31.

[22] K. Calvin, L. Clarke, V. Krey, G. Blanford, K. Jiang, M. Kainuma, E. Kriegler, G. Luderer, P.R. Shukla, The role of Asia in mitigating climate change: results from the Asian modeling exercise, Energy Econ. 34 (3) (2012) 251–260.

[23] L. Clarke, J. Edmonds, V. Krey, R. Richels, S. Rose, M. Tavoni, International climate policy architectures: overview of the EMF 22 international scenarios, Energy Econ. 31 (S2) (2009) S64–S81.

[24] O. Edenhofer, B. Knopf, M. Leimbach, N. Bauer, The economics of low stabilization, Energy J. 31 (Special Issue I) (2010).

[25] G. Luderer, V. Bosetti, M. Jakob, M. Leimbach, J. Steckel, H. Waisman, O. Edenhofer, On the economics of decarbonization — results and insights from the RECIPE project, Clim. Chang. 114 (1) (2012) 9–37.

[26] M. Tavoni, E. De Cian, G. Luderer, J.C. Steckel, H. Waisman, The value of technology and of its evolution towards a low carbon economy, Clim. Chang. 114 (1) (2012) 39–57.

[27] M.G.J. Den Elzen, Exploring climate regimes for differentiation of future commitments to stabilise greenhouse gas concentrations, Integr. Assess. 3 (4) (2002) 343–359.

[28] M. Jakob, G. Luderer, J. Steckel, M. Tavoni, S. Monjon, Time to act now? Assessing the costs of delaying climate measures and benefits of early action, Clim. Chang. 114 (1) (2012) 79–99.

[29] J. Roegelj, D.L. McCollum, A. Reisinger, M. Meinshausen, K. Riahi, Probabilistic cost estimates for climate change mitigation, Nature 493 (2013) 79–83.

[30] UNFCCC, The Cancun Agreements: Outcome of the Work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention, UN Framework Convention on Climate Change, 2010, (FCCC/CP/2010/7/Add.1).

[31] C. Böhringer, E.J. Balistreri, T.F. Rutherford, The role of border carbon adjustment in unilateral climate policy: results from EMF 29, Energy Econ. 34 (S2) (2012) S97–S110.

[32] V.J. Schwanitz, T. Longden, B. Knopf, P. Capros, The implications of initiating immediate climate change mitigation — a review of the potential for co-benefits, Tech. For. Soc. Chang. 90 (PA) (2015) 166–177.

[33] N. Bauer, V. Bosetti, K. Calvin, M. Hamdi-Cherif, A. Kitous, D.L. McCollum, A. Méjean, S. Rao, H. Turton, L. Paroussos, S. Ashina, K. Wada, D.P. van Vuuren, CO_2 emission mitigation and fossil fuel markets: dynamic and international aspects of climate policies, Tech. For. Soc. Chang. 90 (PA) (2015) 243–256.

[34] A. Marcucci, H. Turton, Induced technological change in moderate and fragmented climate change mitigation regimes, Tech. For. Soc. Chang. 90 (PA) (2015) 230–242.

[35] M. Schaeffer, L. Gohar, E. Kriegler, J. Lowe, K. Riahi, D.P. van Vuuren, Mid- and long-term climate projections for fragmented and delayed-action scenarios, Tech. For. Soc. Chang. 90 (PA) (2015) 257–268.

[36] T. Arroyo-Curras, N. Bauer, E. Kriegler, V.J. Schwanitz, G. Luderer, T. Aboumahboub, A. Giannousakis, J. Hilaire, Carbon leakage in a fragmented climate regime: the dynamic response of global energy markets, Tech. For. Soc. Chang. 90 (PA) (2015) 192–203.

[37] L. Paroussos, P. Fragkos, P. Capros, K. Fragkiadakis, Assessment of carbon leakage through the industry channel: the EU perspective, Tech. For. Soc. Chang. 90 (PA) (2015) 204–219.

[38] S. Otto, D. Gernaat, M. Isaac, P.L. Lucas, M.A. van Sluisveld, M. van den Berg, J. van Vliet, D.P. van Vuuren, Impact of fragmented emission reduction regimes on the energy market and on CO_2 emissions related to land use: a case study with China and the European Union as first movers, Tech. For. Soc. Chang. 90 (PA) (2015) 220–229.

[39] E. Kriegler, N. Petermann, V. Krey, V.J. Schwanitz, G. Luderer, S. Ashina, V. Bosetti, J. Eom, A. Kitous, A. Méjean, L. Paroussos, F. Sano, H. Turton, C. Wilson, D.P. Van Vuuren, Diagnostic indicators for integrated assessment models of climate policy, Tech. For. Soc. Chang. 90 (PA) (2015) 45–61.

[40] K. Riahi, E. Kriegler, N. Johnson, C. Bertram, M. den Elzen, J. Eom, M. Schaeffer, J. Edmonds, M. Isaac, V. Krey, T. Longden, G. Luderer, A. Méjean, D.L. McCollum, S. Mima, H. Turton, D.P. Van Vuuren, K. Wada, V. Bosetti, P. Capros, P. Criqui, M. Hamdi-Cherif, M. Kainuma, O. Edenhofer, Locked into Copenhagen pledges — implications of short-term emission targets for the cost and feasibility of long-term climate goals, Tech. For. Soc. Chang. 90 (PA) (2015) 8–23.

[41] F. Sano, K. Akimoto, T. Homma, J. Oda, K. Wada, Analysis of Asian long-term climate change mitigation in power generation sector, 3rd IAEE Asian Conference, Kyoto, Japan, 2012, (http://eneken.ieej.or.jp/3rd_IAEE_Asia/pdf/paper/044p.pdf, last accessed January 2013).

[42] Joint Global Change Research Center, Global Change Assessment Model, www.globalchange.umd.edu/models/gcam(last accessed January 2013).

[43] IPTS, GEM-E3 Website, European Commission Joint Research Centre, http://www.gem-e3.net (last accessed June 2013).

[44] O. Sassi, R. Crassous, J.-C. Hourcade, V. Gitz, H. Waisman, C. Guivarch, IMACLIM-R: a modelling framework to simulate sustainable development pathways, Int. J. of Global Environmental Issues 10 (1/2) (2010) 5–24.

[45] A.F. Bouwman, T. Kram, K. Klein Goldewijk, Integrated Modelling of Global Environmental Change — An Overview of IMAGE 2.4, Netherlands

Environmental Assessment Agency (MNP), Bilthoven, The Netherlands, 2006.

[46] A. Marcucci, H. Turton, Analyzing energy technology options for Switzerland in the face of global uncertainties: an overview of the MERGE model, NCCR Climate WP4 Research Paper 2011/052011. (www.nccr-climate.unibe.ch/research_articles/working_papers/papers/paper201105.pdf, last accessed September 2013).

[47] S. Messner, L. Schrattenholzer, MESSAGE-MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively, Energy 25 (2000) 267–282.

[48] IPTS (Institute for Prospective Technological Studies), Prospective Outlook on Long-Term Energy Systems — POLES Manual, Version 6.1, European Commission Joint Research Centre, 2010. (http://ipts.jrc.ec.europa.eu/activities/energy-and-transport/documents/POLESdescription.pdf, last accessed September 2013).

[49] M. Leimbach, N. Bauer, L. Baumstark, M. Lueken, O. Edenhofer, Technological change and international trade-insights from REMIND-R, Energy J. 31 (2) (2010) 109–136.

[50] V. Bosetti, C. Carraro, M. Galeotti, E. Massetti, M. Tavoni, WITCH: a world induced technical change hybrid model, Energy J. 27 (Issue 2) (2006) 13–38.

[51] A. Lejour, P. Veenendaal, G. Verweij, N. van Leeuwen, WorldScan: a model for international economic policy analysis, CPB Document No. 111, CPB Netherlands Bureau for Economic Policy Analysis, The Hague, The Netherlands, 2006.

[52] H. Waisman, C. Guivarch, F. Grazi, J.C. Hourcade, The IMACLIM-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight, Clim. Chang. 114 (1) (2012) 101–120.

[53] C. Guivarch, R. Crassous, O. Sassi, S. Hallegatte, The costs of climate policies in a second best world with labour market imperfections, Clim. Pol. 11 (1) (2011) 768–788.

[54] M. Meinshausen, S.C.B. Raper, T.M.L. Wigley, Emulating coupled atmosphere–ocean and carbon cycle models with a simpler model, MAGICC6 — part 1: model description and calibration, Atmos. Chem. Phys. 11 (4) (2011) 1417–1456.

[55] D.P. Van Vuuren, J. Lowe, E. Stehfest, L. Gohar, A.F. Hof, C. Hope, R. Warren, M. Meinshausen, G.-K. Plattner, How well do integrated assessment models simulate climate change? Clim. Chang. 104 (2) (2011) 255–285.

[56] M. Meinshausen, N. Meinshausen, W. Hare, S.C.B. Raper, K. Frieler, R. Knutti, D.J. Frame, M.R. Allen, Greenhouse-gas emission targets for limiting global warming to 2 °C, Nature 458 (7242) (2009) 1158–1162.

[57] C. Fischer, R. Newell, Environmental and technology policies for climate mitigation, J. Environ. Econ. Manag. 55 (2) (2008) 142–162.

[58] N. Stern, The Economics of Climate Change — The Stern Review, Chapter 16 , Cambridge University Press, Cambridge, UK, 2007.

[59] J.-F. Lamarque, T.C. Bond, V. Eyring, C. Granier, A. Heil, Z. Klimont, D. Lee, C. Liousse, A. Mieville, B. Owen, M.G. Schultz, D. Shindell, S.J. Smith, E. Stehfest, J. Van Aardenne, O.R. Cooper, M. Kainuma, N. Mahowald, J.R. McConnell, V. Naik, K. Riahi, D.P. van Vuuren, Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, Atmos. Chem. Phys. 10 (2010) 7017–7039.

[60] C. Granier, B. Bessagnet, T. Bond, A. D'Angiola, H.D. van der Gon, G.J. Frost, A. Heil, J.W. Kaiser, S. Kinne, Z. Klimont, S. Kloster, J.-F. Lamarque, C. Liousse, T. Masui, F. Meleux, A. Mieville, T. Ohara, J.-C. Raut, K. Riahi, M.G. Schultz, S.J. Smith, A. Thompson, J. van Aardenne, G.R. van der Werf, D.P. van Vuuren, Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980–2010 period, Clim. Chang. 109 (1–2) (2011) 163–190.

[61] G. Iyer, N. Hultman, J. Eom, H. McJeon, P. Patel, L. Clarke, Diffusion of low-carbon technologies and the feasibility of long-term climate targets, Tech. For. Soc. Chang. 90 (PA) (2015) 103–118.

[62] IMF, World Economic Outlook 2013 Database, International Monetary Fund, Washington DC, United States, 2013. (http://www.imf.org/external/pubs/ft/weo/2013/01/weodata/index.aspx).

[63] M. Tavoni, E. Kriegler, T. Aboumahboub, K. Calvin, G. De Maere, J. Jewell, T. Kober, P. Lucas, G. Luderer, D. McCollum, G. Marangoni, K. Riahi, D.P. van Vuuren, The distribution of the major economies effort in the Durban platform scenarios, Clim. Chang. Econ. 4 (4) (2014) 1340009.

[64] M. Den Elzen, N. Höhne, Sharing the reduction effort to limit global warming to 2 °C, Clim. Pol. 10 (2010) 247–260.

[65] G. Luderer, R.C. Pietzcker, C. Bertram, E. Kriegler, M. Meinshausen, O. Edenhofer, Economic mitigation challenges: how further delay closes the door for achieving climate targets, Environ. Res. Lett. 8 (3) (2013).

[66] T. Aboumahboub, G. Luderer, E. Kriegler, M. Leimbach, N. Bauer, M. Pehl, L. Baumstark, On the regional distribution of climate mitigation costs: the impact of delayed cooperative action, Clim. Chang. Econ. 5 (1) (2014) 1440002.

[67] IEA, World Energy Outlook 2011, International Energy Agency, Paris, France, 2011.

[68] C. Wilson, A. Grubler, N. Bauer, V. Krey, K. Riahi, Future capacity growth of energy technologies: are scenarios consistent with historical evidence? Clim. Chang. 118 (2) (2013) 381–395.

[69] T. Barker, S. Junankar, H. Pollitt, P. Summerton, Carbon leakage from unilateral environmental tax reforms in Europe, 1995–2005, Energy Policy 35 (12) (2007) 6281–6292.

[70] J. Burniaux, J. Oliveira Martins, Carbon emission leakages: a general equilibrium view, OECD Economics Department Working Papers 242, OECD Publishing, Paris, France, 2000.

[71] 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.

[72] P. Criqui, S. Mima, P. Menanteau, A. Kitous, Mitigation strategies and energy technology learning assessment with the POLES model Tech, For. Soc. Chang. 90 (PA) (2014) 119–136.

[73] F. Creutzig, A. Popp, R. Plevin, G. Luderer, J. Minx, O. Edenhofer, Reconciling top down and bottom up modelling on future bioenergy deployment, Nat. Clim. Chang. 2 (5) (2012) 320–327.

[74] 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, Tech. For. Soc. Chang 90 (PA) (2014) 62–72.

Elmar Kriegler is deputy chair of the Research Domain Sustainable Solutions at the Potsdam Institute for Climate Impact Research (PIK), Germany.

Keywan Riahi is leading the Energy Program at the International Institute for Applied Systems Analysis (IIASA, Austria). In addition he holds a part-time position as Visiting Professor at the Graz University of Technology, Austria.

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).

Valeria Jana Schwanitz is a post-doctoral researcher at the Postdam Institute of Climate Impact Research. She is a member of the Global Energy Systems and Macroeconomic Modeling research groups.

Nils Petermann is a project coordinator at the Potsdam Institute for Climate Impact Research. His focus is the EU project AMPERE, dedicated to model analysis of climate change mitigation pathways.

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

Adriana Marcucci is a post-doctoral researcher in the Safety and Environmental Technology Group and the Energy Economics Group in the Paul Scherrer Institute in Switzerland.

Sander Otto works as a researcher in the global change modeling team of Copernicus Institute for Sustainable Development at Utrecht University. He holds a Master degree in Earth System Science.

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.

Shilpa Rao works on the integrated assessment of energy systems, climate change and air pollution at the International Institute for Applied Systems Analysis (IIASA, Austria).

Tabaré Arroyo Currás worked at PIK as an energy specialist with particular interest in climate strategies, policies and economics. He performed research on the role of inflexible carbon markets for climate change mitigation pathways.

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 (NIES), Japan.

Johannes Bollen is working as an environmental economist at the Netherlands Bureau for Economic Policy Analysis (CPB). He has a broad research experience ranging from policy supporting research to pure academics.

Jiyong Eom is a staff scientist at the Pacific Northwest National Laboratory's Joint Global Change Research Institute, USA. He is *now an assistant professor at Sogang University in Seoul, South Korea*.

Meriem Hamdi-Cherif 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 IMACLIM.

Thomas Longden is a Researcher at Fondazione Eni Enrico Mattei (FEEM) and the Euro-Mediterranean Centre for Climate Change (CMCC) in Italy.

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

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.

Fuminori Sano is a research scientist at the Research Institute of Innovative Technology for the Earth (RITE). His research focuses on the assessment of climate change mitigation technologies and policies.

Michiel Schaeffer is a senior scientist and director at Climate Analytics in Berlin, Germany. He is also affiliated with the Environmental Systems Analysis Group at Wageningen University, The Netherlands.

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

Pantelis Capros is a professor of Energy Economics and Operation Research at the Department of Electrical and Computer Engineering of National Technical University of Athens. He is leading the E3M-Lab/ICCS laboratory.

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.

Ottmar Edenhofer is deputy director and chief economist at PIK, where he leads the research on the Economics of Atmospheric Stabilisation. He holds the chair “Economics of Climate Change” at Technische Universität Berlin and is also director of the Mercator Research Institute on Global Commons and Climate Change.