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Induced technological change in moderate and fragmented climate change mitigation regimes

Adriana Marcucci[a b *] and Hal Turton[b]

[a] ETH Zurich, Switzerland

[b] Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

Abstract

Climate change mitigation efforts are currently characterized by a lack of globally coordinated measures and predominantly moderate regional action. This paper compares the results from different Integrated Assessment Models to analyze the impact of such moderate climate change mitigation actions on electricity technology deployment and development, along with the impact of first movers taking stringent unilateral action-specifically, the EU and an EU-plus-China coalition. We find that a fragmented regime with moderate climate and technology targets produces significant emission reductions and changes in the adoption of electricity technologies towards low-carbon alternatives, promoting global technology change. The adoption of more stringent policies by the first movers implies a further transformation of their electricity sectors, but technology deployment outside the coalition is not significantly affected. Furthermore, the results in some models show (1) that first movers can benefit from early action by increased access to low-carbon energy carriers and (2) that delayed action implies the lock-in of carbon-intensive technologies leading to a slower transformation of the electricity sector later.

Keywords: Moderate climate change mitigation policy, technology deployment, technology development, first-mover coalition

1 Introduction

Despite the global nature of climate change, the outcome of the recent Conferences of Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) in Copenhagen (2009), Cancun (2010), Durban (2011), Doha (2012) and Bonn (2013) suggest that the ideal of coordinated and stringent global policy action is not likely to be a near-term reality. Instead, domestic and regional action is taking place to reduce greenhouse gas emissions and deploy low-carbon technologies.

*Corresponding author, madriana@ethz.ch

Several modeling studies have analyzed the effect of such differentiated climate change mitigation policy action. The 22nd Energy Modeling Forum (EMF-22) analyzed scenarios in which BRIC[1] countries delay their mitigation efforts to 2030 and other non-Annex 1 countries to 2050 (Bosetti et al., 2009b; Krey & Riahi, 2009; van Vliet et al., 2009). They found that the delayed participation increases the global cost of mitigating climate change, especially with stringent mitigation objectives or when the non-participating regions have large mitigation potentials. Other studies, not part of the EMF-22, have found similar consequences from second-best climate change mitigation policies (Bosetti et al., 2009a; Edmonds et al., 2008; Keppo & Rao, 2007). In particular, Keppo & Rao (2007) highlight that non-coordinated global action can lead to delays in technological transitions. Bosetti et al. (2009a) discuss the benefits of early action and policy anticipation for developing countries and global deployment of low-carbon technologies. A more recent study from Jakob et al. (2012) concludes that early participation of Annex I countries, China and India can significantly reduce global climate change mitigation costs and those regions can benefit from their early action. Furthermore, they found that the lock-in into carbon intensive energy infrastructure[2] increases global mitigation costs.

However, delayed action is just one of the possible future second-best climate change mitigation policies. Other prevalent policy positions include a wait-and-watch approach while undertaking only moderate action in the near and medium term (such as adopted by the US); or unilateral climate change mitigation action, as it is currently the case in the EU. The consequences of short-term moderate mitigation policies have been analyzed by Bosetti et al. (2009a) and analytically discussed by Olmstead & Stavins (2006). They conclude that the economic costs of long-term stringent climate change mitigation policies can be significantly reduced by undertaking immediate moderate action compared to not acting. Unilateral climate change mitigation policies have also been analyzed in EMF-29 with a particular emphasis on border carbon adjustment (Böhringer et al., 2012) and in other single model studies (e.g. Bosetti & De Cian (2013)).

This paper contributes to the literature by means of an analysis of the effects on technology adoption of a moderate (weak) short- and long-term climate change mitigation policy. Furthermore, since the 2011 Durban Action Platform aims to attain a global agreement not later than 2015 and opens the door to the establishment of coalitions, we also analyze the potential role of unilateral stringent actions in the EU alone or in the EU and China together, and with alternative long-term policies in the rest of the world. A stringent unilateral policy is expected to provide an additional carbon price signal that promotes, in the coalition, the adoption of low-carbon technologies and

[1] Brazil, Russia, India and China

[2] The term technology “lock-in” refers to incumbent technologies preventing the adoption of potentially superior alternatives due to factors such as market characteristics, institutional and regulatory aspects, returns to scale (so that the best/cheapest technology is not chosen), expectation of consumers, among others (Arthur, 1989; Foxon, 2002). However, in the IAMs compared in this study “technology lock-in” refers to energy infrastructure being employed until the end of its lifetime without the possibility of early retirement.

creates incentives for technology innovation (Bosetti & De Cian, 2013; Carraro et al., 2010). However, what happens outside the coalition is not clear. On the one hand, carbon leakage effects[3] could lead to lower fossil fuel prices in the non-participating countries, encouraging increased use of fossil-based technologies. On the other hand, low-carbon technologies, developed due to the mitigation policy in the coalition, can diffuse to other regions through technology transfer instruments such as the Clean Development Mechanism (Dechezleprêtre et al., 2008; Schneider et al., 2008), or international trade and foreign direct investment activity of firms (Bosetti & De Cian, 2013; Keller, 2010). In this paper, we focus especially on the induced technological change in the electricity sector inside and outside the coalition. This technological change is reflected in the adoption of low-carbon electricity technologies, which is directly linked to the achievement of climate change mitigation objectives: in particular, the deployment of renewable-based technologies, nuclear power plants and carbon capture and storage (CCS) options, as described in recent analysis of mitigation scenarios, such as in the IEA Energy Technology Perspectives (IEA, 2010) and the IPCC's Fourth Assessment Report (Sims et al., 2007).

Besides the adoption of low-carbon technologies, both moderate and unilateral stringent climate change mitigation policies can create incentives for technology innovation (Carraro et al., 2010). Technology innovation refers to technical and economical improvements of individual technologies. This process of technological change arises from three interacting factors: experience in the production, deployment and use of the technology; private and public research and development (R&D); and spillovers between sectors, companies, industries or countries (Clarke et al., 2008; Fisher et al., 2007). The first refers to improvements due to so-called "learning by doing". The second factor is related to R&D done by firms, governments, or other entities that lead to technology improvement (Fisher et al., 2007). Finally, technology learning spillovers refer to the transfer of knowledge from a firm, sector or country undertaking innovative activities to another. Technology change, including both technology adoption and innovation due to R&D, can be analyzed ex-post and ex-ante (Carraro et al., 2010). The first type of analysis uses econometric methods and surveys (e.g. on patents) to determine the impact of existing policies on technology development. The second type analyses the effect of future policies using models that include a macro-economic representation of technology change. In these cases, technology change is modeled as the evolution of the investment cost of the technologies, determined either exogenously or endogenously (Clarke et al., 2008). Both endogenous and exogenous approaches have been criticized. The exogenous approach, used for instance in the IPCC's Special Report on Emission Scenarios (Nakicenovic & Swart, 2000), does not link climate change mitigation or technology policy with technological change. While the endogenous approach does, it has been criticized due to the fact that this endogenous technological change is in many cases modeled just for the energy sector and using simplified one-

[3] The IPCC's Fourth Assessment Report defines carbon leakage as "the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries" (IPCC, 2007).

or two-factor learning curves (Clarke et al., 2008). Learning curves are used to describe the behavior of the investment cost of a technology with respect to cumulative production (first factor) and/or investment on research and development (second factor) (Kouvaritakis et al., 2000). This approach is often criticized due to the uncertainty in the learning coefficients, failure to represent other aspects of technology learning, such as spillovers, and for the difficult interpretation of the results. However, given the importance of including a representation of induced technology change in the analysis of long-term mitigation policies, learning curves are still a widely used tool (Clarke et al., 2008). See for example, Bosetti et al. (2009b) or Tavoni et al. (2012). In this paper, we analyze the effect of a moderate climate change mitigation policy on endogenous global technology learning and the additional consequences from unilateral action. Since a moderate and differentiated climate change mitigation policy can be considered as reflecting the current global state, our analysis contributes to understanding technology innovation possibilities arising from uncoordinated global action.

In the first part of the paper we analyze how a moderate (weak) climate change mitigation regime affects global electricity technology adoption and innovation. In the second part of the paper we analyze the effect on technology deployment and development of a unilateral climate action from the EU and an EU-China coalition, beyond the moderate global climate change mitigation policy. For these analyses we use the results of scenario quantifications from different models included in the AMPERE project (Kriegler et al., b); these include primarily integrated assessment models and bottom-up energy system models as described in Kriegler et al. (a). The comparison of various types of models allows us to capture some of the uncertainties pertaining to how the energy-economic system will respond to a given climate regime and identify common robust trends in technology change.

This paper is organized as follows: In the next section we present the moderate climate mitigation policy, and the consequences on technology deployment and innovation; in the third section we describe the results on unilateral climate action and its effects on technology adoption and development; and finally we discuss some policy implications and conclusions of the analysis.

2 Technological change in a moderate climate change mitigation policy

Ongoing negotiations on climate change mitigation seem unlikely to lead in the near future to a coordinated global agreement on greenhouse gas abatement. However, different countries are undertaking moderate actions or have committed to moderate targets following the COP15 in Copenhagen in 2009. To reflect this, we have modeled a scenario (*RefPol*) with moderate (weak) greenhouse gas mitigation and technology targets. Table 1 presents the targets assumed in this moderate action scenario. The technology targets are based on domestic policy targets, while the GHG emissions targets for 2020 are based on an assumed partial realization of the Copenhagen pledges. These

2020 GHG targets are extrapolated after 2020 according to an average GHG intensity reduction, assuming that the different countries will continue with the same level of mitigating effort (Kriegler et al., b).

Table 1: Technology and climate change mitigation targets in the main world countries/regions in the *RefPol* scenario

Region[a] or Country	**Technology targets in 2020**				**Climate change mitigation**			
	Renewables			Nuclear capacity [GW]	GHG reduction in 2020 relative to 2005 or *Base*[b]	After 2020		
	Capacities [GW]		Share electricity			Average GHG intensity improvement [%/year]	GHG per capita reduction relative to 2020	
	Wind	Solar					2050	2100
EU	-	-	20%[c]	-	-15% (2005)	3.0%	-36%	-71%
China	200	50	25%	41	-40% (2005)[d]	3.3%	15%	-50%
India	20	10.3	-	20	-20% (2005)[d]	3.3%	62%	-10%
Russia	-	-	4.5%	34[e]	+27% (2005)	2.6%	4%	-39%
USA	-	-	13%	-	-5% (2005)	2.5%	-31%	-65%
Japan	5	28	-	-	-1% (2005)	2.2%	-16%	-45%
Brazil	-	-	-	-	-18% (*Base*)	2.7%	27%	-1%
Canada	-	-	13%	-	-5% (2005)	2.4%	-26%	-57%
AUNZ	-	-	10%	-	-13% (2005)	3.0%	-38%	-75%
Mexico	-	-	-	-	-15% (*Base*)	2.8%	-6%	-46%
MEA	-	-	-	-	-	1.5%	8%	12%
NAF	-	-	-	-	-	1.5%	48%	125%
SSA	-	-	-	-	-	2.3%	71%	144%
SEA	-	-	15%	-	-	2.1%	110%	168%

[a] AUNZ: Australia and New Zealand; MEA: Middle East; NAF: North Africa; SSA: Sub-Saharan Africa; SEA: Southeast Asia

[b] *Base* is a no-policy scenario that represents a counterfactual case in which no climate change mitigation policies from 2010 are adopted (Kriegler et al., b).

[c] Target on final energy

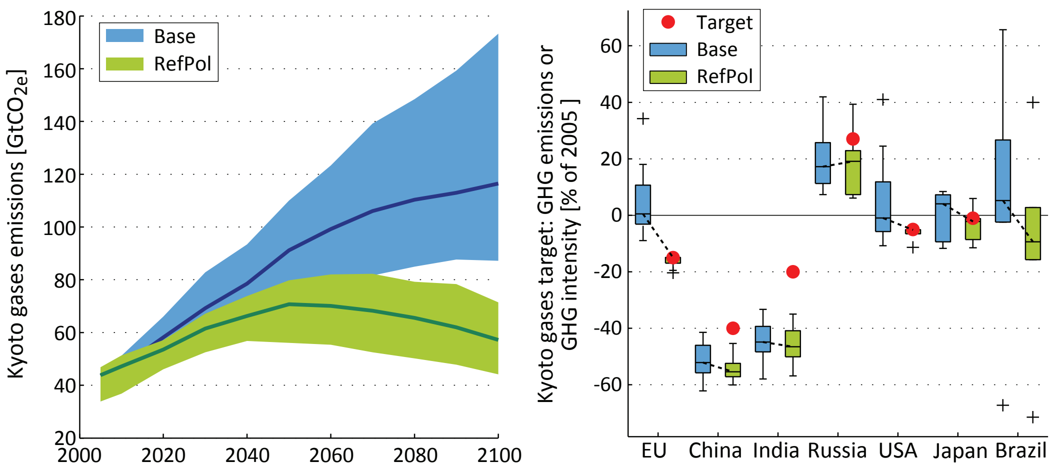
[d] Target on GHG intensity

[e] Target by 2030

This moderate policy scenario was quantified with several energy- economic- environment models covering a range of different modeling approaches, including partial or general equilibrium, perfect foresight or recursive dynamic, and a time horizon until 2050 or 2100. These models comprise: AIM-Enduse, DNE21, GCAM, GEM-E3[4],

[4] We do not report the technology results from GEM-E3, since these results are calibrated to those of the POLES model.

IMACLIM, IMAGE, MERGE-ETL, MESSAGE, POLES, REMIND, WITCH and WorldScan2 (see Kriegler et al. (a) for a detailed characterization of the models). The level of detail and the characteristics of the technologies vary considerably among models, representing some of the significant uncertainty related to the scope, rate, and mechanisms of future technology development. All models adopted harmonized inputs for population and the potential GDP trajectory[5] to improve comparability in the results. Given this harmonization, the regional GHG emissions targets (after 2020) in the *RefPol* scenario are similar for all models.



(a) Global Kyoto GHGs emissions

(b) 2020 Kyoto GHG regional reductions in GHG emissions or GHG intensity for China and India

Figure 1: (a) Kyoto GHGs emissions in *RefPol* and *Base* scenarios; and (b) 2020 reductions in GHG emissions or GHG intensity (according to the targets in Table 1) in *Base* and *RefPol* scenarios. In (a) the dark line represents the mean across the models. In (b) the central mark is the median, the edges of the box are the 25th (q_1) to the 75th (q_3) percentiles, the error bars extend to the minimum and maximum data points not considered outliers, and the outliers (+) are defined as those points that are outside the range $[q_1 - 1.5(q_3 - q_1), q_3 + 1.5(q_3 - q_1)]$[6].

Figure 1a compares the GHG emissions trajectories obtained in the *RefPol* scenario to a reference case without any climate change mitigation policy (*Base*). The total Kyoto gases emissions resulting from the moderate policy are considerably reduced, from an average in 2100 of 116.5 $GtCO_2e$ to 57.1 $GtCO_2e$; this corresponds to a total radiative forcing in the range of 5.1-6.3 W/m^2. Figure 1b presents for different regions the reduction in 2020 of the GHG emissions compared to the corresponding target (presented in Table 1). In EU, USA, Japan and Brazil, the emissions in 2020 in all models are reduced to the imposed 2020 target; while in China, India and Russia emissions in the *Base* scenario are already significantly lower than the target in the *RefPol* scenario.

[5]As an input to the models we use a potential GDP pathway that represents productivity improvements and economic output at constant energy prices.

This is also reflected in the resulting carbon price (see Table 2), which in 2020 is close to zero in those regions where the baseline emissions are lower than the emission targets. Note, the carbon price in all the regions results from applying the regional emission cap obtained from the targets presented in Table 1. These prices are the range of 20 to 200 US$2005/$tCO_2$, with exception of the EU carbon tax in 2100 that goes up to 400-600 US$2005/$tCO_2$. The carbon prices in 2020 are of a similar order of magnitude as the average price in the European ETS market of 5-15 Euros/tCO_2.

Table 2: Mean carbon prices in 2020, 2050 and 2100 in the *RefPol* scenario. The numbers in parenthesis correspond to the 25th and 75th percentiles

Region/ Country	**Carbon price [US$2005/$tCO_2$]**		
	2020	**2050**	**2100**
EU	11.4 (0 - 46.8)	81.1 (50.4 - 145.6)	154.7 (109.7 - 385.2)
China	0.0 (0 - 0)	16.0 (8 - 24.2)	88.7 (45.4 - 123.7)
India	0.0 (0 - 1.5)	19.8 (9.6 - 38.1)	80.3 (61.5 - 142.3)
Russia	0.0 (0 - 1.1)	12.6 (7.9 - 21.1)	56.8 (29.9 - 69.9)
USA	6.9 (0 - 24.3)	37.1 (21.4 - 44.5)	79.9 (33.3 - 126.7)
Japan	3.5 (0 - 10.4)	28.8 (9.7 - 43)	86.9 (56 - 149.4)
Brazil	12.8 (2.5 - 28.8)	21.1 (13.1 - 46.3)	19.0 (0 - 47)

2.1 Technology deployment in a moderate climate change mitigation regime

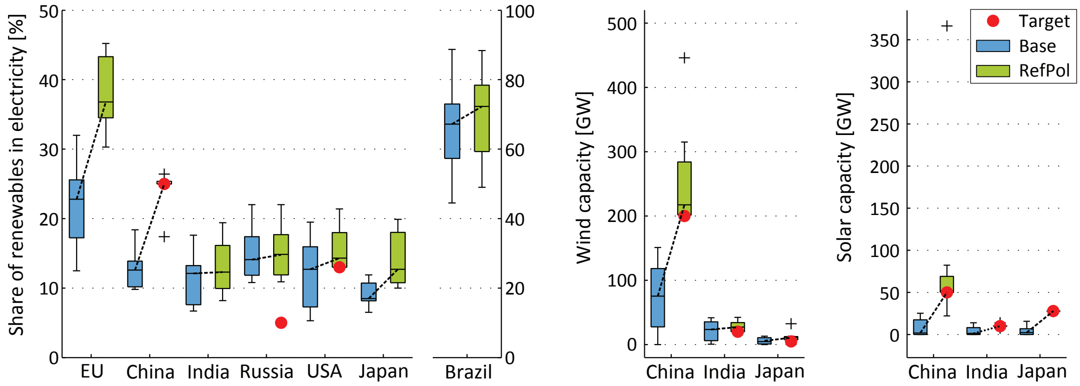
Although the radiative forcing in the *RefPol* scenario exceeds the target of 2.5 W/m^2 considered by the scientific community as the likely maximum radiative forcing to limit global temperature increase to two degrees (using the best estimate of climate sensitivity of 3°C) (Metz et al., 2007), this moderate climate change mitigation scenario already leads to some important changes in global technology adoption[7].

Figure 2[8] compares the share of electricity technologies in 2020 in the *RefPol* scenario to that in the *Base* case, and to the corresponding technology targets (Table 1). Regions can be divided in three categories regarding the interaction between the climate change mitigation and the technology objectives. The first group, including the EU, USA and Brazil, corresponds to those regions in which the climate change mitigation target dominates and induces a significant increase in the share of renewables or

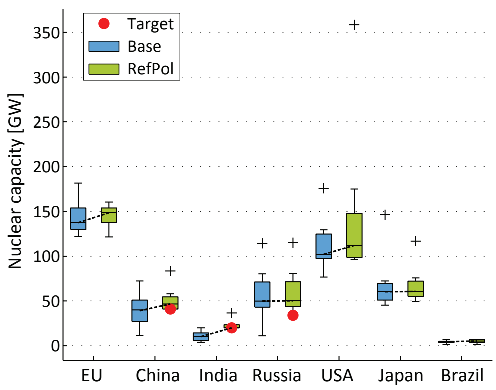
[6] This is valid in all the box plots in this paper.

[7] Note that although our analysis is focused on the electricity sector, the emission reductions in the *RefPol* scenario also include those obtained in the non-electric sectors, such as transport or agriculture.

[8] Fossil-based electricity technologies include oil, coal and natural gas options. Renewable technologies include wind, solar, biomass and hydropower.



(a) Renewable technologies. Left panel: Share of renewables in electricity; Middle panel: Wind Capacity; Right panel: Solar capacity

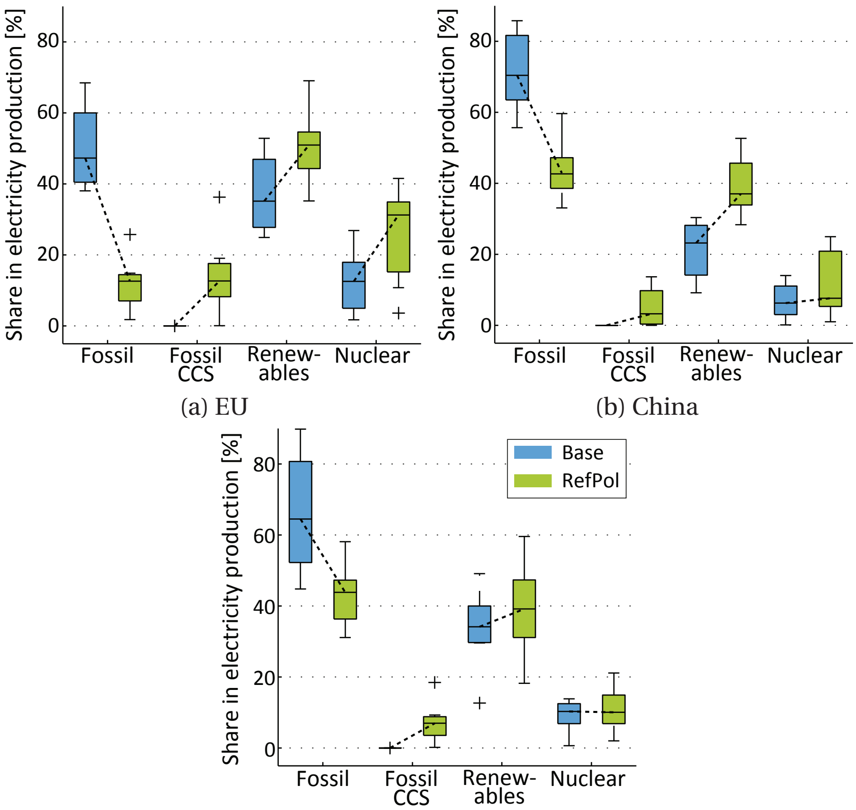


(b) Nuclear technologies. Russia is shown in 2030

Figure 2: 2020 electricity production from low-carbon electricity technologies in the no-policy (*Base*) and the fragmented policy (*RefPol*) scenarios

nuclear capacity (in the EU and USA), even in the absence of a specific technology target as is the case of Brazil in renewables or the USA in nuclear. In the second group, the technology target has the greatest effect, as in China and Japan, and this produces reductions in emissions beyond the targets (see Figure 1b). The third group corresponds to those regions/countries where neither target is stringent enough to produce a significant change in technology adoption, such as India and Russia.

The moderate climate change mitigation regime does not consider additional technology targets after 2020. However, as shown in Figure 3, the regional emission targets have significant effects on technology adoption after 2020, resulting in a shift away from fossil-based electricity technologies without carbon capture and storage (CCS) towards those with CCS. Importantly, the divergence of the modeling results decreases for fossil-based options without CCS but increases for the CCS technologies, showing an agreement among the models in the need to reduce the use of fossil fuels to achieve the reduction in GHG emissions in the moderate regime, but high uncertainty concerning CCS due to the early stage of the development of large-scale plants and issues



(a) EU (b) China

(c) World-EU-China

Figure 3: Share of cumulative production 2030-2100 of electricity technologies in the no-policy (*Base*) and the fragmented policy (*RefPol*) scenarios

concerning policy support and public acceptance (which are not harmonized in the assumptions applied by different modelling teams). Besides the change in the fossil-based electricity technologies, the moderate regime results in a significant increase in the adoption of renewables and, to a minor extent, of nuclear technologies (see Figure 3). As in the case of CCS technologies, the divergence across models increases in the *RefPol* scenario for nuclear power, which also faces barriers related to limited resources, safety concerns and unsolved questions regarding waste disposal.

2.2 Technology learning in a moderate climate change mitigation regime

The current situation of global climate change mitigation is characterized by a fragmented regional action. Each region (or country) has adopted its own mitigation policies, which differ in terms of stringency. In the previous section we showed that despite the lack of global cooperation a moderate climate change mitigation regime can create incentives for the adoption of low-carbon electricity technologies. Since such policies can also support technology innovation (Carraro et al., 2010) in this section we analyze the additional induced technology learning in the *RefPol* scenario compared to those obtained in the *Base* scenario. For this analysis we use the results from two of the models that include endogenous technology learning: REMIND and MERGE-ETL. The REMIND model includes learning-by-doing for wind and solar technologies (see Luderer et al. (2011) for additional detail on the REMIND model). MERGE-ETL, includes global technology learning with two factor curves for some of the electricity technologies, excluding mature technologies such as nuclear reactors and hydropower plants. It models technology innovation as collective evolutionary process using technology clusters (Seebregts et al., 2000). This approach, implemented in MERGE-ETL by Magne et al. (2010), is based on the idea that a number of key components (e.g. gasifier, gas turbines, carbon capture technologies, etc.) are often used across different technologies as shown in Table 3. Thus, the learning process for a given technology benefits other technologies that share the same key components.

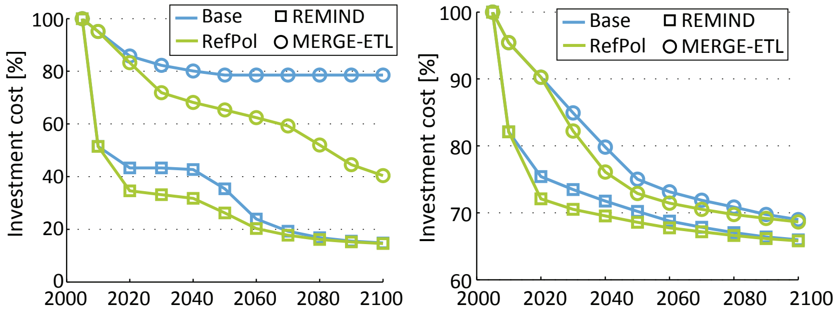
Table 3: Key learning components of electricity technologies in the MERGE-ETL model

Technology	**Key component**								
	Gasifier	Gas turbine	Biomass balance of plant	Coal balance of plant	Advanced coal	Carbon capture[a]		Solar	Wind
						Pre comb.	Post comb.		
Natural gas combined cycle (NGCC)		x							
NGCC (CCS)		x					x		
Pulverized coal (PC)					x				
PC(CCS)					x		x		
Integrated gasification combined cycle (IGCC)	x	x		x					
IGCC(CCS)	x	x		x		x			
Biomass	x	x	x						
Biomass (CCS)	x	x	x			x			
Solar								x	
Wind									x

[a]The capturing of the CO_2 in the production of electricity can be done using mainly two different processes: pre- and post-combustion capture (with oxy-fueling representing a subset) (IPCC, 2005)

To analyze the effect that a fragmented climate change mitigation policy regime has on the innovation of the low-carbon technologies we compare the investment costs of solar and wind, representative low-carbon technologies, in the *RefPol* scenario against the no-policy baseline (*Base*) and the reduction in investment cost of some of the key components in the MERGE-ETL model (see Table 4).

Despite the differences in the modeling of technology learning in REMIND and MERGE-ETL, the moderate policy scenario leads in both models to additional reduc-



(a) Solar (b) Wind

Figure 4: Reduction in investment costs of representative renewable technologies in *Base* and *RefPol* scenarios

tions in the investment costs of renewable-based electricity technologies (see Figure 4). This behavior can be explained by the factors driving technology change in these models: deployment and, in MERGE-ETL, R&D expenditures. As discussed in the previous section and shown in Figures 2 and 3, both the technology and the GHG reduction targets lead to a larger adoption of renewable technologies, which leads to learning-by-doing. In MERGE-ETL, parallel to this process, both targets trigger additional R&D investments that result in improvements to the technologies. In both models, the change in investment costs in the solar technology are larger than those in wind, because wind is already attractive (and learns substantially) in the *Base* scenario.

In Table 4 we present the change in the investment costs[9] in the *RefPol* and *Base* scenarios and the ratio between the reduction in capital costs due to learning-by-doing (LBD) and learning-by-searching (LBS). The moderate climate change mitigation regime results in additional learning of some of the key components that are part of low-carbon options, such as "biomass balance-of-plant" used in biomass electricity technologies; and "CCS pre-combustion" used in IGCC coal and biomass generation options. However, some other key components such as "CCS post-combustion" do not undergo any technology learning in the *RefPol* scenario since they are not supported by the assumed specific technological targets and the climate change mitigation targets are not sufficiently stringent to promote the use of these technologies. Not surprisingly, for some key components there is less learning in the *RefPol* case than in the *Base* scenario (lower cost reductions in Table 4), particularly for those key components that are used predominately by coal-based technologies, e.g. "gasifier" and "coal balance-of-plant".

Moreover, in all key components the reduction in the investment costs due to learning-by-doing is larger than from learning-by-searching (as shown in Table 4), but the impact of R&D expenditures increases with time (the ratio $\rho_{\text{LBD}}/\rho_{\text{LBS}}$ decreases). This is related to the way LBD and LBS operate: firstly, LBD is a byproduct of technology deployment

[9] The investment cost of the x-technology in period t, $I(x,t)$, is calculated as: $I(x,t) = I_0 \times \rho_{\text{LBD}}(x,t) \times \rho_{\text{LBS}}(x,t)$, where $0 < \rho_{\text{LBD}} \leq 1$ and $0 < \rho_{\text{LBS}} \leq 1$ are endogenous factors that represent the reductions in investment costs due to the increase in the production and R&D, respectively; and I_0 is the initial investment cost.

Table 4: Technology learning in the *RefPol* scenario in the MERGE-ETL model: reduction in investment costs by 2050 and 2100 compared to *Base* scenario. The change is reported in percentage points of the initial investment cost of each key component.

	Reduction [%]				***RefPol*** $\rho_{\mathbf{LBD}}/\rho_{\mathbf{LBS}}$	
	2050		2100			
	Base	*RefPol*	*Base*	*RefPol*	2050	2100
Power plants						
Wind	26.2	28.3	32.2	32.5	1.5	1.9
Solar	22.8	35.9	22.8	60.3	2.8	1.5
Key components relevant to one single plant						
Biomass balance of-plant	17.2	23.0	17.2	34.0	6.2	3.2
Coal balance of-plant	33.9	31.4	41.0	37.8	5.4	4.2
Key components relevant to inter-technology learning						
Gasifier	34.3	32.2	41.4	39.5	2.1	1.9
CCS Pre-combustion	0.0	25.6	0.0	45.3		
CCS Post-combustion	0.0	0.0	0.0	0.0		

and does not necessarily have any additional direct cost (unlike R&D), hence it may be a more effective and immediate way of improving the technology[10]; while R&D expenses imply a near-term reduction in either investment or consumption. The larger impact from LbD may also be consistent with the contention that the link between R&D expenditure and innovation is less well understood (and more difficult to measure), and uncertainty in the success of R&D processes can have a large effect in the direction of R&D investments (Blanford, 2009)).

Overall, this analysis shows that despite the absence of coordinated global mitigation action the domestic efforts done by the different regions can promote global technology change through improvements in the production of the technologies and increased R&D. However, there are some limitations in the representation of technology change across the models. For instance, the modeling of technology learning in both MERGE-ETL and REMIND assumes global spillovers in the learning-by-doing process, which requires mechanisms for technology diffusion, such as international trade of technologies and CDM. If this is not the case, significant regional differences in technology costs and availability could arise. Moreover, the spillovers included in MERGE-ETL and REMIND refer to international spillovers; however spillovers between companies or across industries are not represented separately.

[10]Note that we don't model early stages of technology development (e.g. invention and early innovation) where R&D is potentially more important.

Finally, the remaining question addressed in the next section is whether a stringent action from a particular first mover can stimulate additional learning that could then support larger global deployment of low carbon technologies.

3 The effect of unilateral climate change mitigation action in technology diffusion and development

The European Union has taken the lead on climate change mitigation policies, with a target of reducing its greenhouse gas emissions 20% by 2020 relative to 1990 levels (Commission of the European Communities, 2007). On the other hand, China is one of the major world emitters, accounting for 25% of global CO_2 emissions in 2010 (Boden et al., 2013), and with a significant economic and demographic growth in the last decade. In this section we analyze the effect of unilateral climate change mitigation action by the EU and a coalition of the EU plus China on the global deployment and innovation of electricity technologies. We draw on a number of scenarios developed in the AMPERE project model intercomparison (Kriegler et al., b), presented in Table 5. The first two scenarios correspond to *Base* and *RefPol* described in the previous section. The next four scenarios consider unilateral climate change mitigation actions from the EU and the EU+China coalition, with these first-movers either abandoning these targets after 2030 due to lack of action in the other world regions, or the rest of the world joining the coalition between 2030 and 2050, adopting a stringent climate policy. All these scenarios with unilateral action are developed with limited foresight[11] given uncertainty regarding whether unilateral action will later lead to global action. Finally, besides the fragmented policy cases we consider a case with an ambitious global target of 450ppm CO_2-equivalent with full "where" flexibility (*450*), that is, the target is modeled as a global cap on GHG and the models decide the optimal distribution of the abatement among the countries/regions.

Table 5: Moderate and unilateral climate change mitigation scenarios

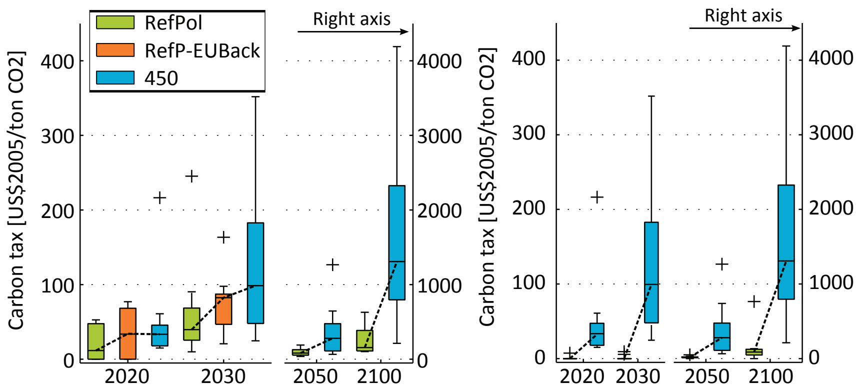
Name	Description	Targets	
		GHG mitigation	Technology
No climate change mitigation policy			
Base	Counterfactual case without climate change mitigation policies from 2010	-	-

[11] Limited foresight is modeled dividing the unilateral action scenario in 2 runs. In the first run the climate policy in the coalition is implemented and extrapolated until 2100 while the other regions use the carbon prices from refPol. In the second run the model variables are locked to the results from the first run until 2030 and the action after 2030 is now modeled. This has been found to have important policy implications, such as delaying investments and higher fossil fuel use (Bosetti et al., 2009b; Keppo & Strubegger, 2010).

Table 5: Moderate and unilateral climate change mitigation scenarios (continued)

Name	Description	Targets: GHG mitigation	Targets: Technology
Moderate climate change mitigation policy			
RefPol	Regional GHG mitigation and technology targets	Targets in Table 1	Targets in Table 1
Coalition abandons unilateral policy after 2030			
RefP-EUBack	The EU has a unilateral policy and abandons it after 2030 for lack of action in the rest of the world	**EU**: Until 2030: EU roadmap: 25% by 2020 and 80% by 2050 relative to 1990 levels. From 2050: Carbon tax from *RefPol* **World-EU**: Carbon tax from *RefPol*	*RefPol*
RefP-CEBack	The EU+China coalition has a unilateral policy and abandons it after 2030 for lack of action in the rest of the world	**EU and China**: Until 2030: Regional carbon tax from *450* scenario. From 2050: Carbon tax from *RefPol* **World-Coalition**: Carbon tax from *RefPol*	*RefPol*
Non-acting regions join the coalition after 2030			
450P-EU	The EU acts unilaterally until 2030 and from 2050 the rest of the world joins the climate change mitigation policy	**EU**: Until 2030: EU GHG emission roadmap. From 2050: EU carbon tax *450* scenario **World-EU**: Until 2030: Regional carbon taxes from *RefPol*. From 2050: Regional carbon tax from *450* scenario	*RefPol*
450P-CE	The EU+China coalition acts unilaterally until 2030 and from 2050 the rest of the world joins the climate change mitigation policy	**EU+China**: Regional carbon tax from *450* scenario **World-Coalition**: Until 2030: Regional carbon taxes from *RefPol*. From 2050: Regional carbon tax from 450 scenario	*RefPol*
Global action			
450	Global climate change mitigation policy	Global target on CO_2e concentration of 450ppm implemented by imposing a cumulative CO_2e emission budget	*RefPol*

In all scenarios, the non-acting regions continue with the moderate climate change mitigation policy regime presented in *RefPol* (modeled as carbon taxes that correspond to the carbon prices obtained in the reference policy scenario shown in Table 2). For the stringent policy, carbon taxes are applied from the *450* case. In the EU, however, the unilateral climate policy is modeled using the EU roadmap[12]. Figure 5 presents the carbon taxes applied in the different scenarios for the EU and China. In the EU, the three taxes have increasingly stringency: Copenhagen pledges (used in *RefPol*), EU emission roadmap (used in RefP-EUBack) and 450ppm CO_2 global target.



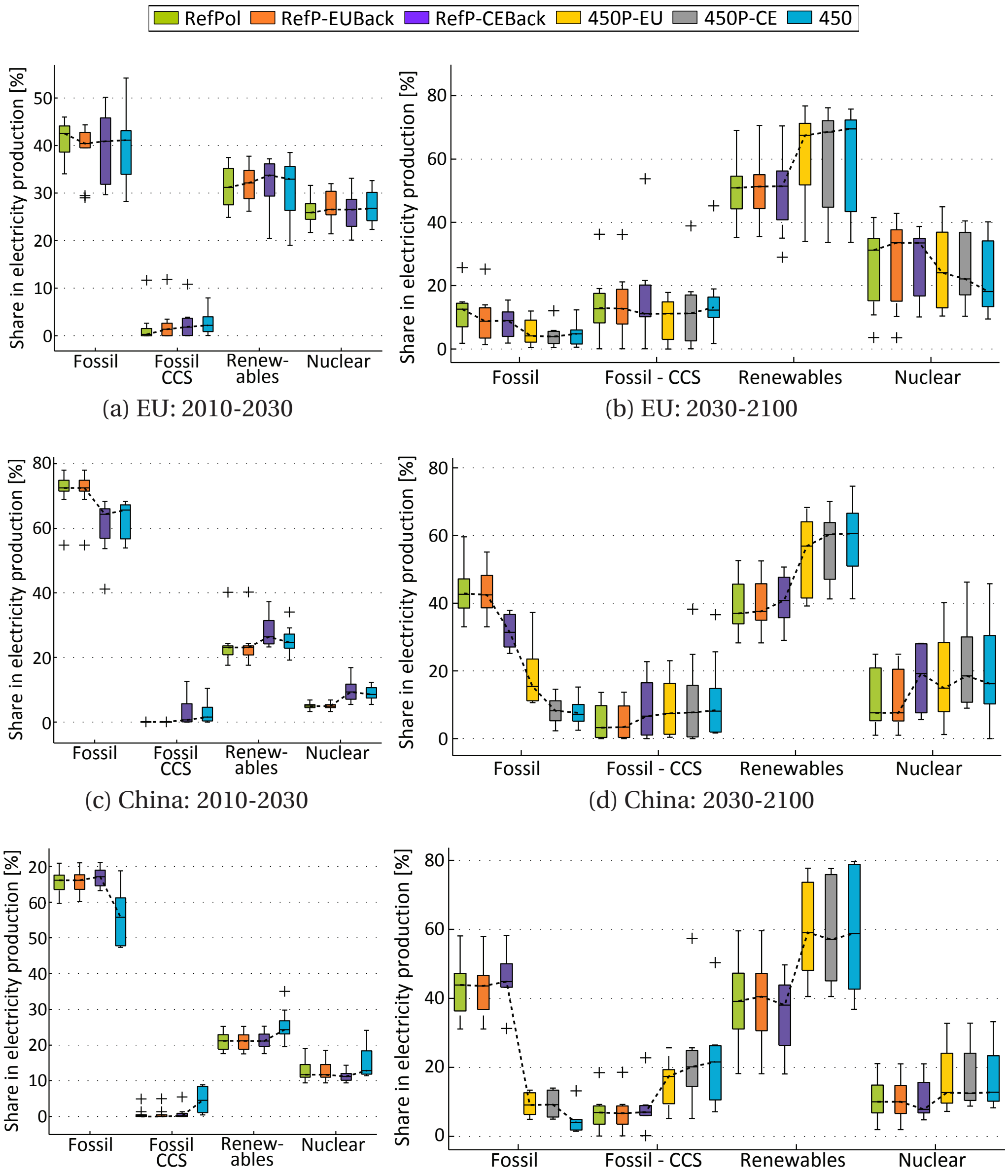
(a) EU (b) China

Figure 5: Carbon prices in the different fragmented climate change policy scenarios

3.1 The impact of unilateral climate policies on technology adoption

In Section 2.1 we showed the significant impact that the moderate climate change mitigation policy regime has on global technology adoption due to both technology targets and climate change mitigation policies. However, when a first-mover coalition decides to act, the consequences outside the coalition are uncertain and two opposite factors could take place: 1) development of low-carbon technologies triggered by the action in the coalition and 2) a reduction in global fossil fuels costs, which could lead to carbon leakage. Figure 6 presents the technology shares in the electricity mix for the different regions, until 2030 (left plots) and after 2030 (right plots). While the coalitions are acting alone, i.e. until 2030, their technology adoption, is characterized by a reduction in the use of fossil fuels, and an increase in CCS, renewables and nuclear. These changes are more significant in China than in the EU since, as shown in Figure 5b, the relative change in the carbon price from the *RefPol* scenario is larger in China than in the EU. However, these changes do not significantly affect technology adoption outside the coalition, where the technology deployment is dominated by the technology targets imposed in the *RefPol* scenario. Just in the MERGE-ETL model, the coalition EU+China uses a significant amount of the uranium resources leading to lower fossil fuel prices, therefore producing some carbon leakage with a slight reduction in the use of nuclear and a slight increase in the use of fossil fuels in the rest of the world. This difference is due to more optimistic assumptions on support for nuclear development in MERGE-ETL.

[12]The roadmap target is a reduction of 25% relative to 1990 levels, more stringent than the target in *RefPol*, which is 15% relative to 2005.



(a) EU: 2010-2030
(b) EU: 2030-2100
(c) China: 2010-2030
(d) China: 2030-2100
(e) World-EU-China: 2010-2030
(f) World-EU-China: 2030-2100

Figure 6: Share of electricity cumulative production in 2010-2030 (left panels) and 2030-2100 (right panels) from fossil, fossil with CCS, renewables and nuclear technologies in the scenarios: *RefPol*, RefP-EUBack, RefP-CEBack, 450P-EU, 450P-CE and *450*

After 2030, results are affected by three main factors including decisions on climate policies, competition for limited resources, and the effects of the early retirement of technologies[13]. The adoption of renewable technologies, inside and outside the coalitions, is mostly determined by the stringency of the climate policies, and the results among models coincide in a higher level of deployment in the presence of stringent climate change mitigation policies. However, the divergence across models is considerable, especially in the rest of the world, due to uncertainties in the future development of renewable resources, which includes regional potentials for wind, solar, hydro, and biomass resources. Biomass is a diverse energy source that can be used to generate electricity or to supply different non-electric demands, such as heating or transportation, and it is among the renewable resources the one assumed to be easily traded. In the ReFP-CEBack and 450P-CE scenario, the early action leads to an increase use and imports of biomass by the coalition, which reduces adoption of biomass-based technologies in the rest of the world (see lower values of renewable-based electricity in RefP-CEBack and 450P-CE in Figure 6f). As with renewable resources, the deployment of fossil-based electricity technologies (with and without CCS) is highly dependent on the climate change mitigation policies[14]. Nonetheless, the assumptions on early retirement applied in the models have an interesting effect on the results. When early retirement is not allowed, the adoption of technologies in the earlier periods leads to more inertia that affects technology deployment after 2030, e.g. in Figure 6d China has higher shares of fossil-based electricity in 450P-EU than 450P-CE. The accuracy of this assumption is highly debatable, however early retirement of technologies poses important questions for investors and policy makers, likely requiring government intervention to coerce and/or compensate plant owners to accept a shorter operation lifetime. Concerning nuclear power plants, the results are also divided according to the climate change mitigation policy with some competition for limited uranium resources, especially when China is part of the coalition and deploys a substantial amount of nuclear power (see scenarios RefP-CEBack and 450P-CE in Figure 6d).

3.2 Technology learning with unilateral climate change mitigation policy

In Section 2.2 we have shown that a moderate policy scenario can promote technology learning despite non-coordinated global climate change mitigation action. In this section we analyze how the action of the first mover coalitions can affect global development of two representative renewable-based electricity technologies. Figure 7 presents the investment costs of wind and solar in the scenarios with unilateral policy with and without action outside the coalition after 2030 and the *450* scenario. The results from REMIND and the MERGE-ETL exhibit important differences in the first 25

[13]The following models allow for early retirement of electricity technologies: AIM-enduse, DNE21, GCAM, MESSAGE and POLES.

[14]The IMACLIM model has very optimistic assumptions for the development of CCS technologies, which result in larger development of fossil with CCS in the EU and the non-acting regions (outlier).

years. While in REMIND the unilateral action in the coalition produces considerable technology learning, especially in the solar technology, in MERGE-ETL the differences of the unilateral scenarios with the moderate policy are not significant. In the case where the EU acts as a first-mover, this is due to relatively little additional renewable-based electricity in the EU, hence little extra LBD. For the case where EU+China acts as a first-mover coalition, the increase in solar and wind production in China is compensated by a decrease outside the coalition where additional fossil-based options are used. Hence, in MERGE-ETL, carbon leakage from the EU+China action reduces the effects on technology learning. After 2030, the two models show similar results with technology innovation depending on the global action to mitigate climate change. Additionally, some lag in the innovation of the technologies is produced by the delayed action in the non-acting regions. These results, like the results in the moderate policy case, assume that technology learning is a global process, which requires technology diffusion from the leading regions to the rest of the world.

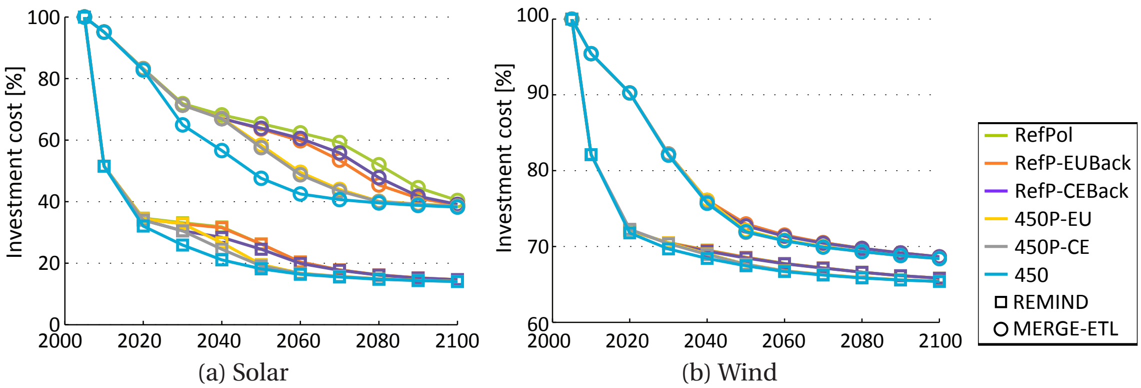


Figure 7: Reduction in investment costs of representative renewable technologies in the scenarios: *RefPol*, RefP-EUBack, RefP-CEBack, 450P-EU, 450P-CE and *450*

Moreover, the results from the two models show significant differences in the assumed learning rates of the technologies, which result in a faster decrease of the investment costs in REMIND compared to MERGE-ETL. The differences in these assumptions reflect the high uncertainty in the development of the technologies and imply, among other aspects, differences in the costs of the moderate climate change policy (see Kriegler et al. (b) for a detailed discussion on the differences in the policy costs among the compared models). However, in the long-run, in both models the costs of wind and solar technologies reach the floor costs (which are specified exogenously).

4 Discussion and conclusions

Although responding to climate change requires global action, so far no effective global agreement has been achieved. Rather, with some exceptions, countries have opted for either moderate or no action on climate change mitigation. This paper contributes to the literature with an analysis of the effect of moderate (weak) regional climate mitigation targets on technology deployment and innovation. Furthermore, we analyze the potential role of first-mover coalitions on the adoption and development of low-carbon technologies.

A climate change mitigation regime characterized by moderate climate and technology targets can lead to an important reduction in GHG emissions and significant changes in the deployment of electricity technologies. Despite the differences across the compared models, there is a significant agreement in the results that show the need to move from fossil-based electricity technologies towards less carbon-intensive options, including carbon capture and storage (CCS), renewables and nuclear power. Both the technology and the climate change mitigation targets play an important role in the observed results. Differences in results across the models are apparent for those models employing more optimistic assumptions on support and development of CCS or nuclear technologies. Furthermore, there is an important variability in the results from the models in terms of deployment of renewable resources, due to the high uncertainty in the potentials. Despite the potential of a moderate climate regime to have a major impact on technology and emissions, it should be noted that even these targets could be seen as ambitious given that governments are focused today on priorities other than climate change, characterized by ongoing poverty and economic crises in many countries.

The results from the compared models show that when the EU or an EU+China coalition undertake more stringent actions, their electricity sectors are transformed towards the use of low-carbon technologies. Outside the coalition, technology is not significantly affected and continues to be determined by the technology and climate policy objectives from the moderate policy. Nonetheless, there are some consequences from first-mover action both within and outside the coalition. First, the competition for low-carbon resources, e.g., uranium or biomass, could in some cases lead to lower deployment of related technologies in the non-acting regions (and similarly, lower global demand for fossil resources could lead to higher deployment of related technologies, i.e. leakage). Second, the delayed action outside the coalition implies continued investment in fossil-based technologies which would require early retirement when stringent climate change policies are implemented; however, investors would likely need to be compensated for this early retirement. Moreover, the first-mover scenarios assume a moderate policy outside the coalition, which drives substantial technology development, including the adoption of low- carbon alternatives. Without the moderate policy in the non-acting regions it is likely that the action undertaken in the coalition would have a larger effect on global technology development. However, this also depends on the assumptions used in the IAMs regarding technology development (and hence future cost), which in some IAMs is assumed exogenously and is thus unaffected by additional technology deployment in the first-mover coalition. While the inclusion in the model comparison of a small number of IAMs with an endogenous representation of technology learning begins to address this, future work with a larger number of such models would support a more systematic analysis of mechanisms by which fragmented action could affect technology choice.

Beyond the scope of the model comparison presented here, it is important to recognize that the first movers face additional risks, such as the uncertainty in the success of developing new technologies and large R&D investments, economic effects of carbon leakage, and the probability that the rest of the world does not join the climate mitigation action, which implies that the first-mover carried out a series of investment and technology changes without the expected leverage on mitigation, potentially crowding out more productive investments. Conversely, the models included in this intercomparison do not generally include a representation of all the mechanisms that may provide an advantage to a first mover (e.g., patents, export trade advantages, political leverage), and hence the endogenous reasons for taking unilateral action. Further, the analysis does not seek to identify benefits and risks associated with other first-mover strategies, such as a technology-development-only strategy (without significant abatement). For such analysis of the advantages and risks of the first mover and the alternative policy strategies (which is beyond the scope of the ex-ante analysis here) other approaches are needed that can account for these benefits (such as technology exports as examined in Kypreos & Turton (2011)) and some of the risks associated with each strategy.

Concerning technology innovation, the regional actions in the moderate climate change regime were seen to promote technological development, reflected in this analysis in the reduction of capital costs of low-carbon technologies. This technology learning is driven by the larger deployment of the technologies and increased R&D expenditures. However, we do not include the uncertainty in the success of R&D processes, which can have a large effect on the allocation of R&D investments. For instance, Blanford (2009) includes stochastic modeling of R&D investments in MERGE, and found that the allocation of R&D investments changes towards innovation in fossil-based technologies with the increase in the probability of failure of the research programs.

The results on technology innovation in the case of unilateral policies show that the first-mover action could lead to some additional technology learning, particularly if less-optimistic assumptions are applied for the support to nuclear power development (considered a mature technology). This finding implies two strategic options for the first-mover coalition: 1. Adopt mature technologies with a promising mitigation potential (e.g. nuclear); and/or 2. Deploy technologies that are more expensive now but have a high potential to induce global technology learning and development. Which is the better strategy depends to a large degree on the likelihood that other regions will join a more stringent global scheme, and the thresholds of mitigation cost which would support such participation, versus the benefits to the region (including co-benefits) of deploying the most regionally suitable technology. Furthermore, the modeling of technology learning in both MERGE-ETL and REMIND assumes a global learning-by-doing process. The extent to which this is a realistic representation depends on the technology, and the effectiveness of mechanisms for technology transfer such as international trade of technologies and CDM. Technologies such as solar PV and nuclear, where there is an international market, may closely exhibit global learning although some regional differences may persist owing to differences in local capacity, or if market power exists. Spillovers may be weaker where regional factors imply significant differences in technology, e.g. biofuel production (due to different feedstocks). In all cases, however, measures to support technology transfer are critical for realizing mitigation targets at lower costs.

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