Technological Forecasting & Social Change 90 (2015) 192–203

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

Carbon leakage in a fragmented climate regime: The dynamic response of global energy markets

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ARTICLE INFO

Article history:
Received 9 April 2013
Received in revised form 2 October 2013
Accepted 3 October 2013
Available online 10 November 2013

JEL classification:
F47
Q54
Q56

Keywords:
Climate policy
Copenhagen pledges
Carbon leakage
Fossil energy markets

ABSTRACT

As a global climate agreement has not yet been achieved, a variety of national climate policy agendas are being pursued in different parts of the world. Regionally fragmented climate policy regimes are prone to carbon leakage between regions, which has given rise to concerns about the environmental effectiveness of this approach. This study investigates carbon leakage through energy markets and the resulting macro-economic effects by exploring the sensitivity of leakage to the size and composition of pioneering regions that adopt ambitious climate action early on. The study uses the multi-regional energy–economy–climate model REMIND 1.5 to analyze the implications of Europe, China and the United States taking unilateral or joint early action. We find that carbon leakage is the combined effect of fossil fuel and capital market re-allocation. Leakage is limited to 15% of the emission reductions in the pioneering regions, and depends on the size and composition of the pioneering coalition and the decarbonization strategy in the energy sector. There is an incentive to delay action to avoid near-term costs, but the immediate GDP losses after acceding to a global climate regime can be higher in the case of delayed action compared to early action. We conclude that carbon leakage is not a strong counter-argument against early action by pioneers to induce other regions to adopt more stringent mitigation.

1. Introduction

Despite the international ambition to keep global warming below 2 °C relative to pre-industrial mean temperature, higher levels of warming are increasingly probable as GHG emissions continue to rise. There is a gap between the stringency of current GHG emission-reduction commitments and long-term mitigation efforts that would be needed to limit warming to 2 °C, or to stabilize atmospheric GHG concentration at 450 ppm CO_2e. Due to the extremely demanding set of challenges that it represents [1,2] a globally binding agreement to stabilize climate change has not yet been reached. In the absence of a global agreement, action on climate change mitigation is emerging in a fragmented manner. A fragmented climate regime is characterized by unequal carbon prices across regions and sectors. A fragmented climate regime, like the Copenhagen pledges [3] can pave the way for a broader and universal regime in the long run [4]. However, in the short- and medium-term, carbon leakage may impact the effectiveness of overall mitigation [5,6].

Carbon leakage is defined as the additional CO_2 emissions of non-mitigating participants (i.e. subjected to a weak reference policy) compared to the CO_2 abatement achieved by pioneering regions (i.e. pursuing additional policy ambition). Carbon leakage is an important aspect of fragmented regimes as it has implications on GDP growth [7], trade [8], employment [9], emissions [10,11] and business decisions [12].

Carbon leakage can take place through four different mechanisms or channels that are activated by policy-induced changes in relative prices [13]: (i) changes of international fossil fuel trade, which has been called the energy channel; (ii) changes of international trade in goods and services that

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http://dx.doi.org/10.1016/j.techfore.2013.10.002

embody carbon emissions generated during the production process, also known as the product market or competitiveness channel; (iii) international trade in factors of production, i.e. the capital market channel; and, (iv) international spillovers, i.e. the technology and policy diffusion channel. Channels (ii & iii) are theoretically explained by the pollution haven or factor endowment hypotheses [14]. The energy channel [15] results from reduced demand for fossil fuels due to unilateral action in emission abating regions, which depresses global energy prices and induces larger demand and consumption in non-abating regions.

Hassler and Krusell [16] assessed qualitatively the welfare consequences of different carbon taxes across, as well as within, oil-consuming and -producing regions, using a dynamic stochastic general-equilibrium model. Their results showed a "perfect leakage" effect (i.e. all emission reductions of one country are off-set by other countries) when carbon taxation was imposed unilaterally, particularly due to a re-allocation effect on oil use from oil producing to oil consuming regions, by lowering the oil price.

Following a regionally specific approach, Böhringer et al. [8] studied quantitatively the impact of specific climate policies by two major economies, Europe and the United States, over global distribution of economic and environmental outcomes. In their study a generic multiregional, multi-sector CGE model of global trade and energy was used and showed a global carbon leakage rate[1] of up to 28% and 10% when Europe and the United States, respectively, reduced emissions due to climate policy. The study highlights the energy channel as the main reason for carbon leakage.

Kuik [13] estimated quantitatively carbon leakage under a fragmented climate policy regime such as the Kyoto Protocol. Using a CGE model, his assessment showed emission increase in non-constrained regions due to increase in energy use and decrease of energy efficiency. He estimated a rate of about 11% due to fragmented climate action.

Bosetti and de Cian [17] studied the cost–benefit considerations that would lead OECD countries to undertake increasing abatement efforts in line with the Copenhagen pledges. In contrast to the previous studies, they used an integrated assessment model with game theoretic structure and detailed representation of the energy sector as well as economic growth. The results showed that when OECD countries followed ambitious targets, free-riding incentives and carbon leakage induced non-members to increase emissions compared to reference baseline. However, the carbon leakage rate decreases with the level of ambition as more ambitious targets by the coalition fostered innovations and technology advancements, and induced reduction of emissions in non-signatory regions due to technology and knowledge transfers.

Böhringer et al. [18] summarized the results of a CGE model inter-comparison exercise aiming at investigating the economic impacts of border carbon adjustment as a complementary instrument to domestic climate policy. In the exercise, a collective CO_2 emission reduction target of 20% below the 2004 levels was imposed on the abatement coalition roughly reflecting post-Kyoto reduction commitments. Based on this, the exercise showed statically a carbon leakage rate between 5% and 19%. The range of leakage effects among the models used in the exercise was traced back and attributed to assumptions about the degree of fossil fuel supply responses and heterogeneity in traded goods, and the regions' flexibility to substitute domestic and foreign goods. The study showed that as model regions can more easily substitute new sources for energy-intensive and trade-exposed goods in response to changes induced by climate policy, the stronger leakage it was. Additionally, the authors highlighted the importance of the competitiveness channel rather than the energy channel for carbon leakage.

McKibbin et al. [19] studied the role of the capital market channel in the context of the Kyoto Protocol. Based on an empirical relationship to represent the saving-consumption decision of households, the study does not find a positive contribution to carbon leakage because the implementation of uni-lateral climate policies induces a net capital inflow for example for the US.

The present study contributes to the scientific literature of carbon leakage via the energy and the capital market channel by studying long-term impacts of additional policy ambition in a fragmented global climate policy regime. Regarding the energy channel, we (i) explore the sensitivity of leakage to the size and composition of abatement action of mitigating regions, focusing on Europe, China and the United States; and, (ii) assess the dynamic leakage effects due to unilateral or joint early action, taking into account its potential evolution in time. The present study also contributes to the literature by analyzing carbon leakage via the capital market channel, which is a novelty, since capital market reallocations are induced by regional interest rate differentials within an intertemporal framework. In this context, we applied the multi-regional energy–economy–climate model REMIND 1.5. REMIND is suitable for the analysis of long-term impacts of fragmented climate policy because it captures the interactions between economy, energy sector, trade and climate mitigation policy.

We start the analysis with scenarios in which the world adopts weak and fragmented policies to limit carbon emissions and non-fossil technology targets. In this setting Europe acts as a front runner by implementing additional policies. Looking at early European unilateral action is interesting as, to date, it has been a leading region in adopting climate policy [20]. For this reason, it is possible to think that Europe is in the position to foster the shift towards low-carbon development pathways, and at the same time motivating other regions to increase efforts towards climate change mitigation. We investigate what is the role for carbon leakage in such unilateral climate action.

Next, we explore the role of partial cooperation of China or the United States in bridging the transition to a global cooperative regime. Thus, this investigation aims to analyze how the size of the pioneering coalition impacts on the role for carbon leakage. Choosing China and the United States as cooperating regions follows three main arguments. Firstly, both countries are top GHG emitters in the world, which makes it interesting to assess given the potential overall environmental effects that could arise when they pursue stringent mitigation in coalition with Europe. Secondly, as China is a fossil resource importer and the United States a potentially significant coal exporter, it is relevant to analyze the impact their emissions abatement would have on global energy trade; particularly, regarding supply changes in fossil fuel rich regions and demand changes in non-cooperating regions. Finally, a broadening of international

[1] In this context, carbon leakage rate is defined as the change in non-abating regions' emissions over domestic emission reduction.

participation to climate agreement in the coming years is expected. As the uncertainty of future negotiation outcomes is significant, analyzing in depth the consequences of diverse climate cooperation possibilities becomes relevant — particularly under current performance of EU, China and the USA as world leaders in the establishment of low carbon frameworks and deployment of clean energy technologies.

We begin Section 2 by briefly describing the REMIND model in its version 1.5. Section 3 lays out an overview of the study design and the different scenarios analyzed. Section 4 discusses the key findings of the study including the environmental effectiveness of unilateral and joint action, the role for carbon leakage and the policy cost implications of fragmented abatement action. Finally, Section 5 draws conclusions and provides an outlook as to policy implications.

2. Methods

This section provides an overview of the REMIND model with a focus on model aspects that are of particular interest for this study. The current version of REMIND builds on previous model versions [21–23].[2]

REMIND is a global multi-regional[3] model of the economy, energy sector and the climate system that computes long-term general equilibrium pathways until 2100. The inter-temporal structure allows for consistent derivation of near-term and long-term scenarios. The international trade of primary energy carriers allows the analysis of policy-induced re-allocation effects. The integration of both dimensions enables the detailed analysis of climate policy proposals within a dynamic and international context.

The REMIND model builds on a macro-economic growth model and a detailed energy sector model. In the following we introduce the framework and mention some details of the energy sector, in particular the fossil fuel sector, as the information is essential for the analysis of policy scenarios presented in this paper.

In each region a Ramsey-type optimal growth model is solved for the intertemporal macro-economic general equilibrium including perfect foresight. The markets for macro-economic aggregates (labor, capital, goods) are in equilibrium.

The macro-economic sector – in addition to capital and labor – demands various types of final energy (electricity, transportation fuels, etc.) that are supplied by the energy sector. The production of final energy requires primary energy, conversion capacities as well as operation and maintenance. Primary energy carriers comprise among others explicit consideration of coal, oil and gas. Energy expenditures are financed from macro-economic output. Since the energy sector model is fully embedded into the macro-economic sector via a hard-link, all energy markets and the capital market are in equilibrium [24].

The various regions are inter-connected by trade flows of the aggregate production goods, coal, oil, gas, and uranium between regions. To solve for the equilibrium of international markets the Negishi approach is applied [25]. It assures in each period that the international markets of traded goods are cleared and the capital accounts are balanced over all regions. Moreover, regions can build up capital account surpluses or deficits over time subject to the constraint that all regional changes in capital account have to be returned to zero by the time of the terminal period. This modeling approach leads to convergence of regional interest rates. CO_2 tax revenue recycling follows a domestic lump-sum approach.

The energy sector in each region represents capacity stocks for the conversion of energy carriers. Investments expand the capacity stocks, but compete with household consumption. Once installed the capacities are subject to technical life-time constraints that can be relaxed by early retirement. Hence, the scale and structure of the capital stock in the energy sector are subject to inertia, and investments into fossil energy conversion technologies imply considerable lock-ins. Several non-linearities are considered including endogenous technological learning, adjustment costs for ramping up specific capacities, and grid and storage penalties for wind and solar electricity generation.

Fossil fuel extraction sectors utilize coal, oil and gas endowments in each region. Endowments[4] are subdivided into different cost grades. These cost grades constitute the long-term extraction costs that are taken from Rogner [26] and Rogner et al. [27]. The extraction from each grade is subject to dynamic constraints that limit the expansion and decline of the supply from each grade. This modeling approach leads to a price formation mechanism that integrates the long-run cumulative extraction costs and the short-run supply curve. Consequently, in each period and region prices will be set by the marginal costs, which in turn exceed average costs.

Regarding fossil fuel trade exporters carry the goods to the border or a harbor, where the fuel enters the global market and exporters receive the world market price. Importers pay the costs for inter-regional transportation and carry the burden of losses for transportation including liquefaction of natural gas. The import distances of each region are measured by taking into account the distances of exporting countries to the import points (like main harbors) of the importing regions [28]. The model is calibrated to replicate the production, consumption and trade statistics. Transportation costs lead to a home bias of consumption that results in a broad diversity of future energy mixes in the regions depending on demand and domestic supply.

Finally, CO_2 emissions are caused by fossil fuel combustion in energy conversion processes without carbon capture and sequestration (CCS). For non-conventional oil the carbon intensity worsens with decreasing fuel quality and lower energy return on energy invested [29,30]. Land-use change emissions follow a baseline path and can be reduced according to a marginal abatement cost function [31]. The same method is applied for non-CO_2 GHGs.

[2] A more technical description can be found here: http://www.pik-potsdam.de/research/sustainable-solutions/models/remind/description-of-remind-v1.5.

[3] It considers 11 regions: the United States; Europe (EU27); Japan; China; India; Russia; sub-Saharan Africa (excl. Republic of South Africa); Middle East, North Africa and central Asian countries; other Asian countries (mostly Southeast Asia); Latin America; and, the rest of the world (incl. Canada, Australia, New Zealand, Republic of South Africa, the rest of Europe).

[4] Endowments comprise reserves and resources of conventional and unconventional coal, oil, and gas.

Table 1
Scenarios and model assumptions[a].

Scenario	Front runner(s)	Global target	Action front runner(s)	Action followers
Base	N/A	None	None	
RefPol	N/A	None	Fragmented regional action (reference policy).	
450	N/A	450	All adopt 450 ppm target and technology targets	
RefP-EUback	Europe (falls back)	None	Europe adopts roadmap until 2030, then falls back to RefPol carbon pricing (emergent in RefPol) by 2050	RefPol carbon pricing (emergent in RefPol)
450P-EU	Europe	None	Europe adopts roadmap until 2030 and then transitions to 450 ppm carbon pricing (emerging under 450 ppm target) by 2050	RefPol carbon pricing until 2030. Transition to 450 ppm carbon pricing by 2050.
450P-E	Europe	None	Europe 450 ppm carbon pricing until 2100	RefPol carbon pricing until 2030. Transition to 450 ppm carbon pricing by 2050.
450P-CE	Europe + China	None	Europe and China adopt 450 ppm carbon pricing until 2100	
450P-UE	Europe + the United States	None	Europe and the United States adopt 450 ppm carbon pricing until 2100	

[a] More information on the different scenarios and their implicit assumptions is available upon request from the authors.

REMIND 1.5 is an insightful framework to analyze carbon leakage in fragmented climate policy regimes for four reasons. First, the model represents international coal, oil and gas markets explicitly. Several global energy market effects can happen, if one region reduces the demand for fossil fuels. (i) Consumption of domestic fuels (like coal in the US) is reduced. The domestic excess production might be delivered to the international market, thus lowering the market price of fossil fuels. (ii) Alternatively, no effect on international markets is felt due to prohibitive transport costs to market the domestic resource internationally. (iii) Emission abatement might not only affect consumption from domestic sources, but also reduce the demand for fossil fuel imports from the international market, again lowering the market price for fossil fuels. This may lead to higher imports of other regions or higher consumption of exporters. Second, REMIND derives the demand for fossil fuels endogenously because it models the full value chain from fuel to energy sector to final consumers. If fossil fuel prices decrease, the non-abating regions increase their demand up to the point, where the marginal product equals the price. This leads to substitution effects in the energy sector and the macro-economic sector as well as macro-economic growth effects that are fully captured in the model. Third, if climate policies reduce the domestic return on capital, savings can flow to other regions, which increases GDP abroad and generates domestic incomes. The first two mechanisms relate to the energy channel for carbon leakage whereas this mechanism relates to capital markets. Finally, the REMIND model represents learning of renewable electricity technologies with interregional spillovers, which can lead to negative carbon leakage via the technology diffusion channel if non-abating regions take advantage from lower investment costs by also deploying such technologies.

3. Study design

To examine carbon leakage via the energy channel under different climate policy configurations, we perform three sets of simulations, following the AMPERE study design on staged accession scenarios (Kriegler et al., this volume; Table 1 [32]). First, we model three reference scenarios used as benchmarks for assessing additional mitigation policies of pioneering countries in a fragmented policy regime: (i) a default baseline without climate policy; (ii) a fragmented climate policy reference (RefPol), with detailed representation of regional 2020 emission reduction targets, non-fossil technology targets and GHG intensity improvement rates after 2020 [5]; and, (iii) a climate policy benchmark with a level of stringency comparable to the 450 ppm CO_2e concentration target (equivalent to a radiative forcing of 2.6 W/m^2). This was implemented in terms of a cumulative CO_2 budget of 1500 Gt CO_2e for the period 2000–2100 (following the study design) enforced on top of the technology targets, and considering non-CO_2 Kyoto gas reduction at the carbon equivalent price induced by the budget.

The second scenario set considered European unilateral action by adopting a carbon price trajectory consistent with the European roadmap.[6] This scenario included two variations, a variant in which the Europe abandons the roadmap after 2030 and returns to the reference climate policy by 2050 (reconsideration case: RefP-EUback), and a variant in which all regions (including Europe: 450P-EU) adopt the carbon price trajectory that emerged under the 450 ppm benchmark (Europe succeeds).[7] Finally, we run three additional climate policy scenarios where a set of front runner regions starts off on a 450 ppm carbon pricing trajectory, and is joined by the rest of the world after 2030.[8] In these scenarios, all regions converge to a global carbon price trajectory that emerged under the 450 ppm benchmark until 2050. We consider three different front runner compositions — the EU27, EU27 joined by China, and EU27 joined by the United States. In summary, a total of eight scenarios are investigated framing the unilateral and joint climate action exercise presented here.

[5] The emission targets are implemented via carbon taxes. Hence, regions that only implement weak climate policies should, in principle, be able to increase their emissions if global fossil fuel prices fall due to more ambitious emission reductions in other regions. This would be impossible, if the policies were implemented via strict emission caps.

[6] Refers to the Europe 2020 energy and climate roadmap [33]. For this purpose, Europe follows ca. 25% (2020), 40% (2030) and 80% (2050) Kyoto gas emission reduction targets relative to 1990 emissions (for simplification, including LULUCF; the original roadmap proposal excludes LULUCF). Additionally, 20% renewable energy in final energy was assumed.

[7] The two scenarios differ from a full implementation of the European roadmap by 2050, in that none of them achieve an 80% emission reduction in 2050. While in the first variant, RefP-EUback, the road map is dropped after 2030, in the second, 450P-EU, the transition to the 450 ppm carbon pricing leads to more than 80% reductions.

[8] Differently to the "Europe succeeds" case, in this set of runs Europe adopts an early 450 ppm carbon price trajectory rather than the roadmap.

4. Results

4.1. The baseline, reference policy, and immediate action scenarios

The baseline scenario without climate policy is dominated by fossil energy use with 2020 Gt CO_2 of cumulative emissions from fossil fuel combustion and the industry sector[9] for the period 2010–2050. In this case, demand of primary energy from fossil fuels, increasing from 430 EJ/yr in 2010 to 935 EJ/yr in 2050, locks in the energy system into a high usage of carbon intensive technologies. The increase in energy-related emissions is particularly driven by the high energy intensity of economic output, and high amount of CO_2 emitted per unit of primary energy consumption.

In the 450 ppm scenario, the cumulative CO_2 emissions for the period 2010–2050 are reduced to 1160 Gt CO_2. In contrast to the baseline scenario, the 450 ppm case is characterized by a post-2010 decarbonization process fostered by switching carbon-intensive energy carriers to low-carbon or carbon free energy carriers such as renewables, and the limited use of CCS technologies from 2030 onwards. For instance, non-biomass renewable energy increases from 14 EJ/yr in 2010 to 100 EJ/yr in 2050, and primary energy used in combination with CCS reaches 221 EJ/yr by 2050. Overall, comparing both scenarios, baseline and 450 ppm, the cumulated CO_2 emission gap towards the 450 ppm target is about 860 Gt CO_2 for the 2010–2050 period. The gap increases dramatically after 2050.

In terms of the reference policy scenario, emission reduction and low carbon technology capacity targets in 2020 stimulate global cumulated emission savings up to 11.2 Gt CO_2 for the 2010–2020 period i.e. 3% compared to the baseline without climate policy. Additionally, post-2020 emission intensity improvement targets, foster further carbon abatement and lead to a total cumulated emission reduction of 150 Gt CO_2 for the period 2010–2050 i.e. 8% compared to the baseline. Thus, the reference policy leads to a reduction of the cumulative emission gap towards the 450 ppm target by 18% to 710 Gt CO_2 by 2050.

4.2. Impact of European unilateral action on the energy sector

Fig. 1a shows the impact of EU adopting the 2050 roadmap unilaterally (scenarios 450P-EU and RefP-EUback) on the level of CO_2 emissions in Europe. From 2010 to 2020, difference in emission levels between reference policy and unilateral action cases is minimal.[10] During this period, the major driver towards CO_2 abatement is the increase in renewable energy (biomass playing an important role) and nuclear energy in primary energy demand. After 2020, Europe implements higher CO_2 abatement in the roadmap scenario than in the reference policy as it approaches the 2030 emission target. By 2030, energy related carbon intensity is reduced by partially shifting fossil primary energy demand towards biomass (11 EJ/yr) incl. biomass CCS technologies (2 EJ/yr), non-biomass renewables (7 EJ/yr), and nuclear energy (4 EJ/yr).

From 2030 onwards the European unilateral cases bifurcate as they follow different carbon price trajectories. In the 450P-EU, i.e. "Europe succeeds" scenario, post-2030 CO_2 abatement leads to an increasing penetration of biomass CCS technologies; by 2050, they amount to 18 EJ/yr and over 25% of total primary energy demand. On the other hand, in the RefP-EUback, i.e. the reconsideration scenario, a partial re-carbonization takes place by higher consumption of fossil fuels towards mid-century (particularly oil) and a decrease in biomass primary energy consumption. However, pre-2030 mitigation action locks in the high use of nuclear and biomass CCS technologies by 2050, preventing CO_2 emissions from returning to reference policy levels even when the roadmap is abandoned.

Fig. 1b shows the impact of European unilateral action on the level of global CO_2 emissions. Looking at the global picture, emissions reduced due to European unilateral action contribute only a very small fraction to the total abatement needed in order to reach emission levels required in the 450 ppm scenario, at least until 2030. Global cumulative emissions until 2030 are reduced by 2.8 Gt CO_2 compared to the reference policy case, which closes the gap to the 450 ppm case by a mere 2.2%. Post-2030, the "Europe succeeds" case closes the gap between the reference policy case and the 450 ppm case mostly due to the fact that all regions start adopting the 450 ppm carbon price trajectory and, consequently, implement more stringent climate mitigation. Delayed accession of all regions to the 450 ppm climate policy regime adds to European unilateral emission reductions and achieves global cumulative CO_2 abatement of 360 Gt CO_2 compared to the reference policy during the 2010–2050 period. In this respect, emission reduction post-2030 takes place through energy system transformation with increasing penetration of non-fossil low carbon technologies (140 EJ/yr including nuclear) and CCS technologies (115 EJ/yr including biomass CCS technologies).

4.3. Impact of early mover action on the energy sector

Here and in following sub-sections we analyze different schemes of uni-lateral and joint action. For the purpose of comparability we assume the identical carbon tax path following the 450 ppm scenario that is implemented in early mover countries across the different scenario configurations. The technology targets until 2020 are also adopted.

Fig. 2 shows the impact of the setup of the early mover coalition on the level of global CO_2 emissions. Compared to the reference policy scenario, joint front runner action of Europe–China, i.e. 450P-CE, leads to a global cumulated reduction of 6% (50 Gt CO_2) during the period 2010–2030. The emission gap between the reference policy case and the 450 ppm-e case of 116 $GtCO_2$ is closed by 39%. By contrast, a front runner coalition of Europe and the United States, i.e. 450P-UE, leads to smaller emission abatement compared to 450P-CE but still higher than in the case of European unilateral action (450P-E); together, early action by Europe and the United States leads to a global cumulated reduction of 2% (15 Gt CO_2). The gap to the 450 ppm-e case is only closed by 12% until 2030.

Fig. 3 shows the emission reductions in response to the carbon price for the three early mover regions for the period 2020–2050. As the carbon price trajectories are the same in

[9] Unless stated differently, emissions will refer to CO_2 emissions from fossil fuel combustion and industry.

[10] The European CO_2 emission reductions from fossil fuel and industry in 2020 relative to 2005 levels in the reference policy and the road-map scenarios are 20.3% and 21.4%, respectively.

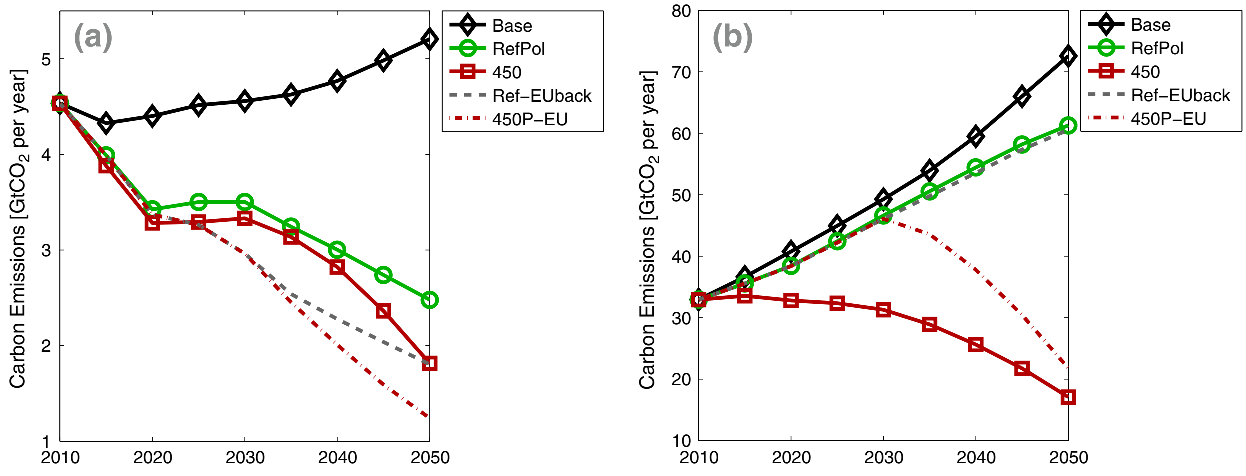

Fig. 1. CO_2 emissions from Fossil Fuels and Industry: a) Europe and b) world.

these regions, the emission reductions are directly comparable. It shows that Chinese emissions respond more strongly to the carbon tax than US emissions. Although both China and the US are comparable in size of primary energy demand, the level of carbon intensity per unit of energy in China (84 Mt CO_2/EJ in 2010) is higher than in the United States (66 Mt CO_2/EJ in 2010). Thus, China (in 450P-CE) abates more than the United States (in 450P-UE) as it has cheaper abatement options with respect to both energy efficiency improvements and fuel switching in the electricity sector. China also reduces its larger coal use in the industry and residential sectors that has a smaller marginal product than electricity. These differences result in emission reductions in China that are significantly larger than those in the US.

The high carbon prices in the 450P-CE scenario push the decarbonization of electricity and liquids production in China. Consequently, a rapid shift from coal to lower carbon content carriers (such as gas from 5 EJ/yr in 2010 to 33 EJ/yr in 2030) and also oil for liquids production (from 15 EJ/yr in 2010 to 34 EJ/yr in 2030) is triggered. In the liquid fuel production mix, 1.2 EJ/yr of additional oil derived liquids partially substitute 1.4 EJ/yr of liquids from coal that emerge in 2030 for the reference policy case. In the 450P-UE scenario, abatement in the US takes place through decarbonization of electricity production by substituting coal with nuclear. The high carbon pricing in both scenarios pushes the deployment of non-biomass renewables. It increases from 2 EJ/yr in 2010 to 10 EJ/yr in 2030 in China (in 450P-CE) and from 1.5 EJ/yr in 2010 to 4 EJ/yr by 2030 in the United States (in 450P-UE).

After 2030, the emission gap to the 450 ppm scenario is closed by further abatement due to the global adoption of 450 ppm carbon pricing, achieving global cumulative CO_2 abatement of 465 Gt CO_2 and 350 Gt CO_2 respectively compared to the reference policy during the period 2010–2050. If the rest of the world did not join the global carbon pricing regime and China and EU27 switched back to the reference policy case, cumulative emission reduction until 2050 would only be 148 Gt CO_2. Hence, the benefit of reduced global warming delivered by early action will only be small if the rest of the world is not induced by the front runners to raise the stringency of its emission reductions.

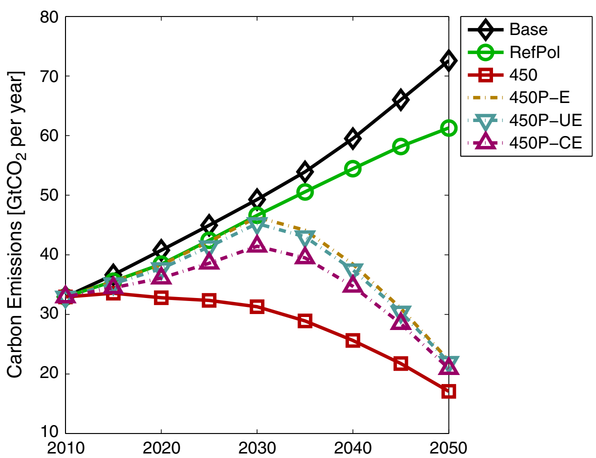

Fig. 2. Global CO_2 emissions from Fossil Fuels and Industry across joint mitigation action scenarios.

4.4. Carbon leakage due to additional policy ambition in a fragmented policy regime

Fig. 4 shows the cumulated carbon leakage resulting from European unilateral and joint EU–China and EU–US climate action. In the 450P-E scenario, we observe that European unilateral emission abatement is partially offset by increasing cumulated emissions in non-abating regions, from 135 Mt CO_2 in 2020 to 375 Mt CO_2 in 2030 (Fig. 4a). From 2020 to 2030, however, the total global leakage rate[11] varies between 10% and 16% as European emission reductions increase over this period. Major regions where emissions leak are Middle East and North Africa (5%) and the United States (3%) during 2020–2030. Additionally, we observe that in 2020, China has

[11] It is defined as the change in cumulated CO_2 emissions in non-acting regions over emission reduction in early mover regions.

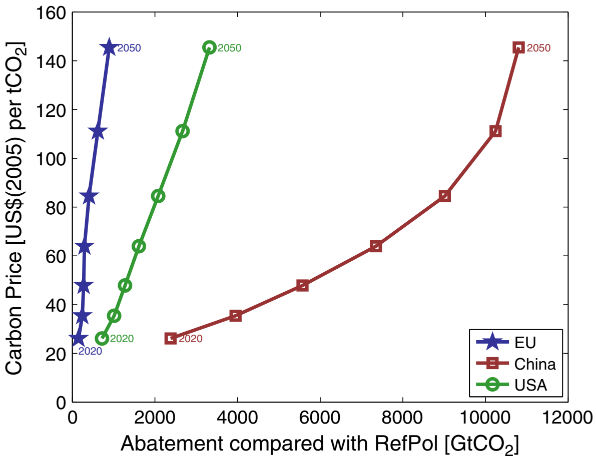

Fig. 3. Common carbon price in Europe, the United States and China plotted over regional emission reductions compared to policy baseline for the period 2020–2050. The markers locate the situtations in 5 year time steps.

a leakage rate of 4% which decreases to 1% by 2030. India shows a negative leakage rate.

Carbon leakage in the 450P-CE scenario increases with time, in contrast to the 450P-E scenario. In this case, joint Europe–China abatement is partially offset by increasing cumulated emissions in non-abating regions from 750 Mt CO_2 in 2020 to 4600 Mt CO_2 in 2030 (Fig. 4b). The carbon leakage rate evolves from 6% in 2020 to 9% in 2030. The most significant emission increases occur in Sub-Saharan Africa (3%) followed by Southeast Asia (2%) as well as Latin America and the US (1%) during the 2020–2030 period. Middle East and North Africa (MEA) show negative leakage in the 450P-CE scenario due to two effects. First, China consumes more gas and reduces coal use; additional international gas demand reduces domestic consumption in MEA. Second, as China consumes more oil for liquids production, thus substituting for coal, additional demand for oil reduces domestic oil consumption in MEA, as it exports more oil to China. Overall, negative leakage in MEA is mainly driven by the first effect, i.e. de-carbonization in the power sector by reduced consumption of gas and increasing electricity generation from renewables.

Finally, in the 450P-UE scenario, we observe a fairly stable leakage rate in the range of 12–13% during the period 2020–30. During this timeframe, offset emissions of non-abating regions increase from 430 Mt CO_2 in 2020 to 1900 Mt CO_2 in 2030, at about the same rate as emission reductions in the US and Europe increase (Fig. 4c). In this scenario, key regions with increased emissions are China (4%), Middle East and North Africa (3%) and Sub-Saharan Africa (1%) during the period 2020–2030.

In general, we observe that as the size of emission abatement increases, the amount of absolute leakage also increases. Then, total cumulated leakage is highest when Europe and China act as a coalition and lowest when Europe acts unilaterally. Two reasons can explain this behavior. Firstly, in the 450P-CE case, China performs major abatement by substituting coal in secondary electricity and liquids production with lower carbon content energy carriers i.e. gas and oil.[12] China's abatement puts downward pressure on global coal demand suppressing the world market price and inducing larger consumption in the rest of the world, particularly, in emerging economies with fast growth of energy demand as well as very low carbon prices in the reference policy case; e.g. Sub-Saharan Africa and Latin America. For instance, by 2030, the coal world market price is lower in the 450P-CE (1.9 $US\$_{2005}$/GJ) than in the reference policy (2.2 $US\$_{2005}$/GJ). Uni-lateral action by EU does not affect the world coal price. Secondly, as China's demand for oil and gas rises, imports by other regions decline, e.g. Southeast Asia, which then partially shifts to coal imports as a substitute for electricity and liquids production; this leads to higher emissions due to different carbon intensities of these alternative secondary energy production technologies. The price changes of oil and gas are only small for the scenarios with partial adoption of the 450-e carbon tax.

In the case of the 450P-E scenario, we observe two interesting effects: (i) the United States increases its emissions and (ii) India reduces them. As Europe reduces demand for oil and gas, the world market price of these energy carriers decreases. As oil and gas get more accessible, other regions increase their imports e.g. India which then partially substitutes coal with oil and gas for liquids and electricity generation respectively. Then, as India, a big coal importer, reduces demand for coal and world prices decline, exporters have more incentive to consume the resource domestically e.g. the United States partially shifts its production of liquids from biomass to coal, slightly increasing its carbon intensity in liquid fuel production. Additionally, gas increases its share in the electricity mix at the expense of other sources e.g. non-biomass renewables originally in place due to implementation of renewable share targets for electricity production.

Finally, in the 450P-UE scenario, we observe that the United States abates emissions by reducing domestic coal consumption and by reducing demand for oil and gas imports; domestic coal production is partially re-allocated to exports. This phenomenon affects world market prices due to increase in supply, making coal more attractive to importers such as China. Then, higher coal consumption fosters higher level of emissions in those regions. On the other hand, the United States decreases demand for oil and gas, partially substituting it with higher consumption of liquids from biomass and partially with production of electricity from nuclear and renewables. Decreasing world demand for oil and gas due to joint action performed by Europe and the United States gives incentives to exporters to shift to domestic consumption e.g. Middle East and North Africa.

Carbon leakage across scenarios takes place mostly due to fossil fuel substitution in secondary energy conversion. Fig. 5 compares regional differences in carbon intensities in electricity and liquids production across scenarios.[13] We observe that from all scenarios, the 450P-CE is the one that induces the most significant shifts. We further observe that, as China reduces its carbon intensity in electricity and liquids production (demand for coal reduces), exporters increase domestic consumption, moving towards a more carbon intensive generation of electricity (e.g. the United States) and liquids (e.g. Sub-Saharan Africa and Russia). It is worth highlighting that, as Europe is

[12] Electricity from gas in China by 2030 is 8 EJ/yr in the reference policy scenario, whereas it is 16 EJ/yr in the 450P-CE scenario; liquids from coal are 1.4 EJ/yr in the reference policy case, and zero in the 450P-CE case by 2030.

[13] Bauer et al. [34] compares these findings against those produced by other models.

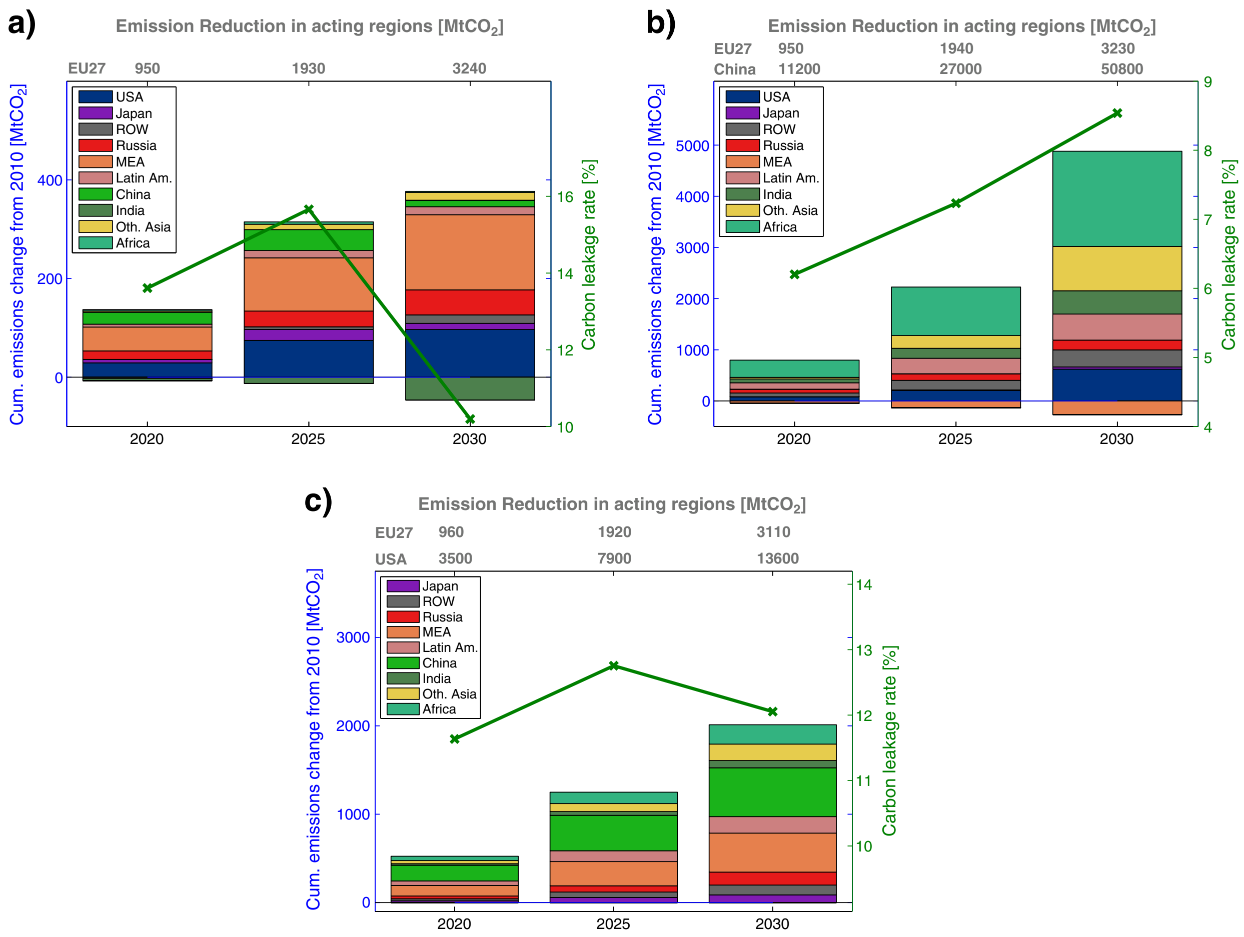

Fig. 4. Cumulated carbon leakages (i.e. emissions increase in non-abating regions; in left hand scale) and carbon leakage rates (i.e. change in non-abating regions' emissions over domestic/joint emission reduction; in right hand scale) in fossil fuels and industry across joint mitigation action scenarios: a) 450P-E, b) 450P-CE and c) 450P-UE.

performing stringent mitigation action in all scenarios, it does not experience such induced inter-fuel substitution effects. In this study, technology spillovers related to technology learning are not observed. This is due to the fact that low carbon technology deployment is already pushed in the reference policy due to the technology targets. As a result the additional cost reduction from early mover action is small and not large enough to induce further technology diffusion to other regions.

The persistence of carbon leakage over time depends largely on the context determined by the abatement chosen by the front runners. If EU (and the US) acts the reduction of oil and gas contributes a considerable part of the emission abatement in these regions. The hydrocarbons are also subject to relatively high fossil fuel market leakage as they find new uses in other world regions. The initial effect is relatively large in 2025 leading to a high carbon leakage rate, but with additional abatement the carbon leakage saturates and therefore the carbon leakage rate decreases. If China acts as a pioneer, then the reduction of coal use leads to relatively small carbon leakage in early years. Only the increasing energy demand of Africa, which is relatively scarce in energy endowments, will absorb an increasing share of the coal that is not consumed in China anymore and therefore the carbon leakage rate increases over time.

In summary, emission abatement by early movers implies leakage through the energy channel that increases with the absolute level of abatement. The carbon leakage rates are moderate, though, and range between 6% and 16%. Also carbon leakage rates are not necessarily increasing over time and, some regions can even contribute negatively to the overall carbon leakage. Carbon leakage rates through the energy channel are limited for three reasons. First, fossil energy demands in non-acting regions saturate and also substitution possibilities with non-fossil energy carriers are limited. Second, the reference policy case includes moderate carbon pricing also in the regions that initially do not participate in a global climate regime, which penalizes carbon leakage to these regions. Third, fossil fuels are internationally not fully tradable goods because of transportation costs. Hence, effects on international markets from demand changes in one region are dampened. In the end, both insights suggest that even when unilateral action persists over time, the amount of carbon that leaks to latecomer regions is limited.

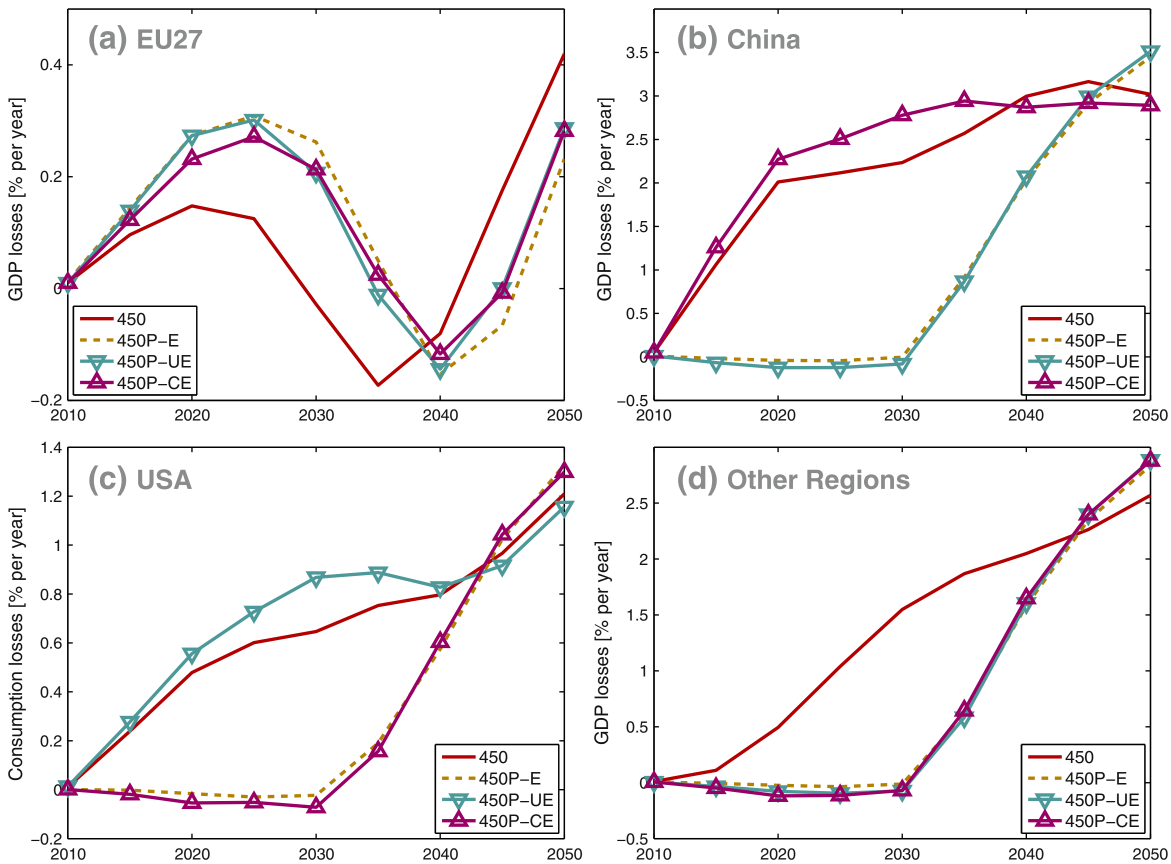

Fig. 5. Carbon intensity in secondary energy production of electricity and liquids across joint mitigation action scenarios.

4.5. Macro-economic implications of fragmented climate action

We finally analyze the macro-economic effects of additional climate change mitigation policies. We first focus on the relative impacts on regional GDP for the various scenarios to assess the regional mitigation cost dynamics. Second, we look at regional GDP changes as a driver of carbon leakage via the capital market channel.

Fig. 6 shows regional policy costs over time expressed as GDP losses relative to the reference policy for all scenarios in percentage terms. For the different regions and scenarios three essential findings are derived.

First, Europe in Fig. 6(a) incurs a higher GDP loss, when acting alone than in the case of globally coordinated action.[14] Acting in alliance with the US or China instead of acting unilaterally leads only to a negligible reduction of GDP losses. Similarly, the GDP of China and the US is less affected by the carbon tax when implemented globally than when these countries act as pioneers. Hence, in case Europe, China and the US decided to implement a carbon tax, their GDP would be less affected, if other regions applied the tax as well.

Second, the levels of GDP losses are very different across regions. Europe would only experience a small additional GDP loss; until 2030 the additional net present value GDP loss is 0.2%. The additional losses for the US, and particularly China, are higher. The early application of the carbon tax reduces the net present value of GDP until 2030 by 0.5% in the USA and by 2% in China compared to the reference policy case. The remarkable difference between China and the US highlights on the one hand the importance of energy supply to support the economic development process. In addition, China will undertake larger emission reductions than the US due to the larger availability of cheap abatement options (Fig. 3).

Third, the ramp-up of GDP losses for China approximately has similar magnitude for an immediate adoption of 450 ppm carbon pricing or for convergence to 450 ppm levels between 2035 and 2050. This is different in the US and other regions, where the ramp-up of GDP losses is faster in the delayed tax case; Fig. 6(c–d). In all three – China, the US and other regions – the delayed tax leads to somewhat higher annual GDP losses in 2050, although the taxes converge to the same level in that year. The relative GDP loss for the US over the 20 year period after raising the carbon tax is higher when the tax ramps up after 2030 (period 2030–50; 0.6% GDP loss), than when jumping to the 450 ppm level immediately (period 2010–2030; 0.5% GDP loss). In China, instead, the corresponding loss is 0.2%-points smaller, which indicates that the carbon tax exerts a stronger economic impact in earlier stages of economic development.

[14] The significant dip of the time paths around 2035/40 is due to the specific policy proposals combining emission limitations and technology policies. For instance, in Fig. 1(a) it can be seen that the emissions stabilize in the 450-e scenarios after 2020 and are forced to decrease again after 2030.

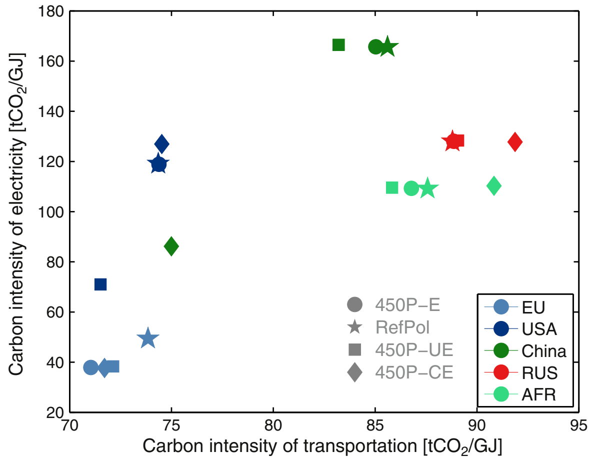

Fig. 6. Policy cost as GDP losses across European unilateral and joint mitigation action scenarios for: a) Europe, b) China, c) the United States and d) the rest of the world.

Next, we focus on GDP changes due to international capital markets as a driver of carbon leakage. Table 2 shows the GDP changes for pioneering and late-coming regions as well as the ratio between both (bottom row). The changes are due to re-allocation of investment flows on the international capital market and the re-allocation of fossil fuels across regions. The figures show that the ratio of GDP redistribution exceeds the carbon leakage rate. This means that international capital markets react relatively flexible. However, it does not imply that the capital market is the major driver behind carbon leakage. For instance, in the scenario with China and EU acting together the cumulative carbon emission in 2010–30 increases by 1% in late-coming regions compared with the reference policy case. The corresponding increase in cumulative GDP is less than 1‰, and therefore international re-allocation of economic activity is not a major driver of carbon leakage as stated in [6]. In summary, as mitigation efforts rise along the 450 ppm carbon price trajectory, macroeconomic output is suppressed across scenarios. This is mainly because (i) less primary energy originating from a reduction of fossil energy supply generates less GDP and (ii) the energy sector relies on higher cost technologies and attracts more financial resources that crowd out other investments. Though capital markets are highly flexible the reallocation of global investments is not a significant driver for carbon leakage.

5. Conclusions

Given the challenges to international cooperation on mitigating climate change, a number of climate policies have been implemented by various countries and regions, while others remain on the sideline. The heterogeneity of climate policy approaches has given rise to an internationally fragmented climate policy regime. Subsequently, global emission externalities such as carbon leakage have emerged as an important topic within the climate change mitigation debate.

This study illustrates the incidence and consequences of carbon leakage as an effect of early action in a fragmented climate policy regime. For this analysis, the REMIND integrated assessment model of the global economy, energy sector and the climate system is used to evaluate the environmental effectiveness and economic implications of unilateral and joint mitigation efforts. Overall, the main scope of this paper is to examine the role of carbon leakage via the energy channel, i.e. the increase in fossil fuel use in regions with weaker or non-existent climate policies due to more stringent mitigation action in other regions. The study also includes the capital market channel of carbon leakage.

We derive four main findings from our study. First, a reference policy scenario extrapolating fragmented action at current levels of ambition into the future will reduce emissions only modestly compared to the idealized case of immediate cooperative action on reaching a 450 ppm CO_2e stabilization target (compare Blanford et al. [35]). Therefore, a pioneering region adopting more stringent emission reductions may be needed to strengthen climate mitigation. We show that the main impact on additional emission reductions does not come from the early mover action itself, but from the rest of the world following up with strengthening their abatement effort post 2030. Thus, a pioneer in adopting more stringent mitigation action needs to be particularly concerned with its ability to induce others to follow.

Second, the carbon leakage rate via the energy channel is limited to below 16% of the additional emission reductions from more stringent abatement action by pioneering regions. This result holds for different sizes and compositions of the early mover coalition. The carbon leakage mechanisms include the reduction of coal use in pioneering regions, or indirectly in other regions via knock-on substitution effects from reduced gas use in abating regions, leading to increased coal consumption in the rest of the world. While the type of mechanism and the regions that increase their fossil fuel consumption vary with the early mover coalition, the general result of limited leakage stands. This implies that carbon leakage, at least via the energy channel investigated here, is not strongly impacting the emission reduction gains from early mover action, and does not permanently increase the lock-in into fossil fuel infrastructure in other regions. It therefore does not provide a strong counter-argument against adoption of more stringent mitigation efforts by pioneering regions.

Compared with the scientific literature that mainly focused on the competitiveness channel the upper limit of 16% carbon leakage rate due to the energy market channel is small (Babiker

Table 2
Redistribution of GDP from early mover action. Numbers measure the change of cumulative net present value of GDP 2010–30 in bn.US$ (2005). The discount rate is 5%/yr. Other regions comprise those regions that are not part of the early mover coalition in the specific scenario. The bottom row reports the ratio of GDP increases in late-coming regions divided by the GDP reduction in the front-runner countries.

		450P-E	450P-CE	450P-UE
GDP reduction of early movers	EU	440	380	420
	China	–	2200	–
	USA	–	–	900
GDP increase of late-comers	Other regions	120	360	320
	Ratio	28%	14%	24%

[36]; Babiker [37]; Bernstein et al. [38]; Bollen et al. [39]; Burniaux and Oliveira-Martins [40]; Burniaux and Truong [41]; Gerlagh and Kuik [42]; Kuik and Gerlagh [43]; Light et al. [44]; Manne and Richels [45]; McKibbin et al. [19]). In the REMIND model the representation of international fossil fuel markets is highly flexible and fossil based energy conversion technologies can easily replace alternatives. Hence, fossil fuel suppliers can, in principle, find new demands easily, if demand is reduced due to uni-lateral climate policies. Carbon leakage via the energy market channel is mainly limited due to trade costs of fossil fuels and demand for final energies in non-abating countries. In the present study also the carbon prices of the moderate climate policies dampen the carbon leakage. Studies focusing on the competitiveness channel usually depend on the choice of trade elasticities with higher elasticities implying larger carbon leakage rates. In this study fossil energy trade is not limited in a similar way, and therefore limitations should imply even smaller carbon leakage rates.

Third, we observe that the re-allocation of emissions due to carbon leakage depends mostly on the energy system structure of the region that takes abatement action i.e. whether the region is a fossil resource importer (e.g. Europe), exporter (e.g. the United States) or de facto carbon intensive economy (e.g. China). We conclude that carbon leakage is a dynamic effect that mostly depends on (i) demand response of fuel importers to price changes, (ii) inter-fuel substitution possibilities and (iii) transportation cost barriers in the fossil fuel market.

Regarding the economic implications of fragmented climate action we confirm the assertion that early mitigation action leads to short-run GDP losses for the first movers, but delayed implementation of the carbon tax can lead to larger losses after the introduction of the tax. The larger tax shock can act as a significant barrier to take more stringent action and therefore delaying action might further impede the adoption of more ambitious carbon tax levels in the long run. We also find reallocation of GDP between early mover and late-comer regions triggered by the international capital market, but this is not a major driver of carbon leakage. This result is, however, different to the result of McKibbin et al. [19] who identified the converse effect on carbon leakage for the US.

Several caveats apply to the analysis here. First, the REMIND version used for this study does not take into account bilateral fossil fuel trade, but assumes a global pool trading scheme. Considering bilateral (or multilateral) trading reduces the flexibility of fossil fuel owners to redirect their supplies as some regions reduce their demand. Hence, this improvement might lead to lower leakage rates. Second, the study focused only on the energy channel of carbon leakage, although macro-economic substitution effects between energy, capital and labor were accounted for. Expanding the analysis of dynamic leakage in staged accession scenarios to a larger set of leakage channels, particularly including the re-allocation of energy intensive industries, would help to better constrain the full carbon leakage effect. It is worth mentioning that technology spillovers related to technology learning are not observed in this study.

We conclude from the results that the value of individual regions or coalitions adopting more stringent climate action rises or falls with their ability to induce others to follow suit. Thus, while global cooperation on climate mitigation may prove illusory in the short run, credible and strong mitigation action by major countries can help to keep the door open for future global action to stabilize climate change as carbon leakage effects are limited.

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 265139 (AMPERE).

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