



# Impact of fragmented emission reduction regimes on the energy market and on CO<sub>2</sub> emissions related to land use: A case study with China and the European Union as first movers

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## ABSTRACT

In recent years, an approach based on voluntary pledges by individual regions has attracted interest of policy-makers and consequently also climate policy research. In this paper, we analyze scenarios in which the EU and China act as early-movers in international climate policy. Such a situation risks leakage between regions with ambitious emission reduction targets and those with less ambitious targets via fossil-fuel markets, displacement of heavy industry and land-use consequences. We examine some of these factors using the IMAGE model. While IMAGE does not include all mechanisms, we find the leakage rate to be relatively small, about 5% of the emission reductions in the EU and China. The far majority occurs via the energy market channel and the remainder through land-use change. Reduced oil prices due to less depletion forms the key reason for this leakage impact.

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## 1. Introduction

Many studies have argued that an economically optimal climate policy should be based on an international regime in which a wide range of different countries participate [1–3]. Current climate negotiations, however, seem not to be leading in that direction. Instead, as part of the Copenhagen Accord and the Cancun Agreement, an alternative system based on voluntary pledges has emerged, at least temporarily. The pledges indicate that countries have very different ambitions with respect to mitigation action [4]; in fact, a large number of countries do not participate in emission reduction [5]. Although the pledge-based approach has advantages in terms of ease of implementation, a disadvantage is that policies of individual countries can become much less effective [1], one reason being that the total volume of emissions targeted by the

policies is considerably lower than it would be if there were universal commitment. Moreover, differences between countries in the efforts made to achieve emission reduction may trigger various interactions between countries, for instance via the energy markets, including the relocation of economic activities to non-participating countries and the enhanced energy demand in non-participating countries in response to lower fossil fuel prices [4–8].

In the literature, these interactions are often referred to as leakage, as they may weaken the effectiveness of the climate policies of individual countries. Examples of leakage include the relocation of economic activities to non-participating countries and the enhanced energy demand in non-participating countries in response to lower fossil fuel prices. Climate policies can, however, also result in 'negative leakage', i.e. emission reductions in non-participating countries such as induced technology learning [9].

In the AMPERE project, various consequences of fragmented international climate policies are studied based on a scenario-

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**Table 1**

Scenarios discussed in this paper.

Brief name	Description and main characteristics
<i>Base</i>	Scenario assumes that no climate policies are implemented and is based on the assumptions of the OECD Environmental Outlook [12] in which population <sup>a</sup> and GDP <sup>b</sup> are both harmonized.
<i>RefPol</i>	Fragmented regime: a weak policy scenario with regional emissions reduction targets for 2020, based on the Copenhagen pledges, followed by a constant regional greenhouse gas intensity improvement in line with the 2020 pledges (Appendix B), this scenario is used as a reference scenario.
<i>450</i>	All regions immediately adopt a 450 ppm target and technology targets.
<i>RefP-CEback</i>	Fragmented regime with EU27 and China as first mover. After 2030, weak climate policy is discontinued.
<i>450P-CE</i>	Fragmented regime in which the rest of the world joins EU27 and China in 2030 by adopting the carbon tax of the 450 scenario.

<sup>a</sup> Population is harmonized by using the medium population scenario of the UN 2010 Medium Term Projection [13].

<sup>b</sup> The GDP projections were constructed following a method developed in the RoSE project [14].

based model comparison exercise [10]. The scenarios compare coordinated policy regimes to regimes in which the EU and/or China are the first to move ahead toward more ambitious policies. Among the different world regions, it is the EU that has most clearly expressed its ambition by aiming for an emission reduction by 80% by 2050 (to achieve a 2 °C reduction target), and to consider action even if international agreement is not reached. China's long-term policies are less clear, but the country has committed to supporting international climate policy. Together, the EU and China currently account for about a third of global CO<sub>2</sub> emissions. In this context, it is interesting to consider what the impacts would be of a scenario in which either the EU or China—or both—would implement ambitious climate policies, whereas other countries would implement modest policies.

In this paper we analyze how a situation in which international climate policies are fragmented and the EU and China are first movers, influences greenhouse gas emissions outside the EU and China in the energy system and in relation to land use. To do so, we use the IMAGE integrated assessment model. The analysis focuses on the following questions:

- How do the policy regimes impact global greenhouse gas emissions?
- How do these policies impact the greenhouse gas emissions change in the energy and land use system — both directly and indirectly?

Below, we first describe the methodology and scenario experiments (Section 2). In Section 3 we report the results. Finally, in Section 4 we summarize the conclusions.

## 2. Methodology

### 2.1. The IMAGE integrated assessment framework

The IMAGE integrated assessment model examines the possible development of global environmental problems based on different assumptions about socio-economic development and policy [11]. The model consists of several coupled models that describe the energy and land-use system and also represent components of the Earth's natural system, such as climate and natural vegetation. Most of the subcomponents of IMAGE are simulation models, i.e. a set of rules determines the future developments of, for instance, the energy system and land use.

In the energy system, different technologies compete for a share in investment flows on the basis of their relative costs. The focus of the model is on describing long-term dynamics. Long-term decisions in the energy system are assumed to be governed by the relative costs of various technologies. These long-term costs are assumed to be determined by two processes: depletion and technology dynamics, which in turn are driven by production (cumulative or otherwise). The model also describes international trade of fossil/bio-fuels, by taking account of the relative costs (including transport costs) in different supply regions.

An important feature of the IMAGE model is that it is also able to describe changes in land use. Key inputs in the land-use model are the demand for production of food, feed, bio-energy, and animal products. Assumptions on technology and management and on the impact of local climate and soil conditions on yields are used to determine the land requirement and allocate it to a 0.5° × 0.5° grid cell. The need to meet an additional demand for products from agriculture leads to additional CO<sub>2</sub> emissions from land-use change.

A key component of the mitigation strategies in the IMAGE model is bio-energy. This energy is used in the energy system in the form of solid bio-fuels in the industrial, power, and hydrogen sectors, and in the form of liquid bio-fuel in other end-use sectors (particularly transport) and the production of feedstock. In the power sector, in the industrial sector, and also in hydrogen production, bio-energy use can be combined with CCS, providing the option of so-called negative emissions. In IMAGE, bio-energy is assumed to be produced from crop residues and dedicated crops. The potential for the latter is based on the land model used in IMAGE: bio-energy can be produced on abandoned agricultural land and extensive grassland. Costs depend on the yields in each grid cell, regional income levels (as a proxy for labor costs), and changes in the level of technology.

There are three possible interactions between regions in the context of climate policy. First of all, the regions are interconnected via fossil fuel trade markets. Reduced fossil fuel consumption in countries that are implementing climate policy is likely to depress international prices for fossil fuel, because it slows down the depletion of reserves. This may, however, boost fossil fuel consumption in non-participating regions. Second, technological learning is assumed to be shared across regions. Therefore, strong mitigation activities in some regions may reduce the costs of non-fossil technologies. Third, participation is likely to impact the bio-energy markets, as countries may opt

to import bio-energy from other regions. This could not only affect emissions via bio-energy prices, but also directly enhance land-use emissions.

Finally, it should be noted that in IMAGE, energy prices are influenced solely by long-term processes such as slower depletion. In the real world, climate policy may also influence fossil fuel prices by creating overcapacity, in turn leading to potential leakage. With respect to bio-energy production, it should be noted that the model assumes that bio-energy crops are grown only on abandoned agricultural land or natural grassland, so that CO<sub>2</sub> emissions as a result of land use change will be relatively low. For both reasons, the figures reported in this article should be regarded as conservative.

## 2.2. Scenarios

As indicated in the Introduction section, the scenarios used in this study, form part of the scenario design of the AMPERE project [10]. Table 1 presents the scenarios that we use for our analysis. In the baseline scenario (*base*), we look at the possible development of greenhouse gas emissions in the absence of climate policies. The population and economic developments of this scenario are based on the AMPERE protocol [10]. The assumptions on the energy sector and land use are largely based on the baseline scenario developed by the IMAGE team for the OECD Environmental Outlook [12]. The reference scenario (*RefPol*) looks into the impacts of the short-term climate policies formulated by different countries and their possible extension in the 21st century [10]. The scenario has been extended beyond 2020 by assuming similar decarbonization rates as in the preceding period.

The 450 scenario is a uniform climate policy scenario that aims at reaching 450 ppm CO<sub>2</sub>-eq by 2100, by immediate global introduction of a carbon price. Two fragmented policy regime scenarios build on the reference scenario (*RefPol*) but diverge after 2020 by introducing more stringent climate policies in the EU (*EU*) or in the EU and China (*CE*) in the period up to 2030, followed by either returning to the *RefPol* scenario (*back*) or converge to the 450 scenario taking on stringent reductions in all regions (*450P*).

Here, we focus on leakage impacts, by comparing the results of the *RefPol* and *RefP-CEback* scenarios.

## 3. Results

### 3.1. Results of the different scenarios in terms of greenhouse gas emissions

In the baseline scenario, *base* (without climate policy), global primary energy demand is expected to triple by the end of the century, predominantly fueled by coal and gas. This trend obviously leads to an increase of fossil fuel CO<sub>2</sub> emissions. Also CO<sub>2</sub> emissions related to land use and the non-CO<sub>2</sub> emissions contribute to higher greenhouse gas concentrations. In total, global emissions are projected to more than double throughout the 21st century (Fig. 1a).

In the reference policy scenario *RefPol*, the extrapolation of current policies limits the emission increase to 56 Gt in 2020 and to 69 Gt in 2050. After 2050, the emissions decline slowly (Fig. 1a). Based on the current policies (Appendix B), especially the emission trajectory of the EU contrasts shows a strong reduction from the baseline (13% in 2020 and 46% in 2050) (Fig. 1b). In China, emissions initially increase steeply in the *RefPol* scenario, but emissions decrease in 2nd half of the century as a result of a declining population and the assumed policies (Fig. 1c).

In the default 450 ppm scenario emissions are reduced drastically in all regions, stimulated by global carbon prices of 110 (US\$ 2005/tonne CO<sub>2</sub>) in 2050 and 210 (US\$ 2005/tonne CO<sub>2</sub>) in 2100. The overall reductions in 2050 compared to 2000 are nearly 50%. By 2100, emissions have become virtually zero for total greenhouse gases. These reductions are achieved by a combination of energy efficiency improvement, additional use of bio-energy and renewables, fossil fuel substitution and the reduction of non-CO<sub>2</sub> gas emissions.

Finally, we introduce the two early-mover scenarios. In the *RefP-CEback* scenario, it is assumed that the more stringent climate policy aiming for 450 ppm in the EU and China is abandoned gradually between 2030 and 2050. Interestingly, the results of this scenario show that emissions remain below the reference level for much longer, as a result of the inertia of the energy system. In other words, investments in alternative technologies can lead to considerable path dependency (for a further discussion of path dependency and carbon lock-in, see Ref. [15]). The same result, but in the opposite direction, can be seen for the global emissions of the *450P-CE* scenario: here, other countries join the EU and China in the 2030–2050 period, but still emissions remain above the 450 scenario for a very long time.

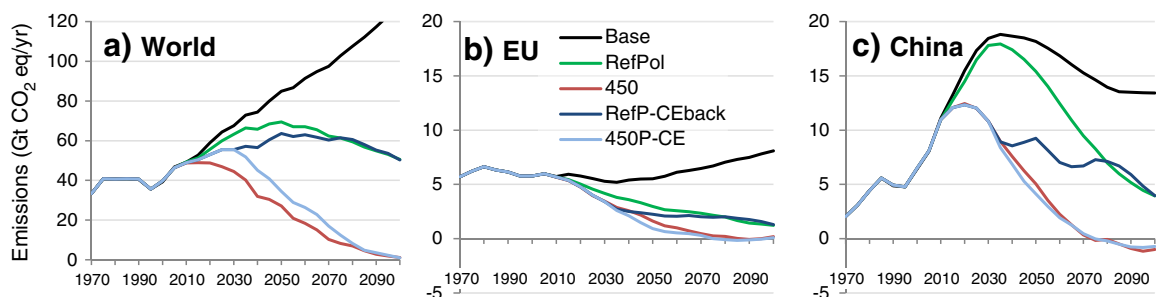


Fig. 1. CO<sub>2</sub> eq greenhouse gas emissions for the world (a), the EU (b) and China (c) for all scenarios.

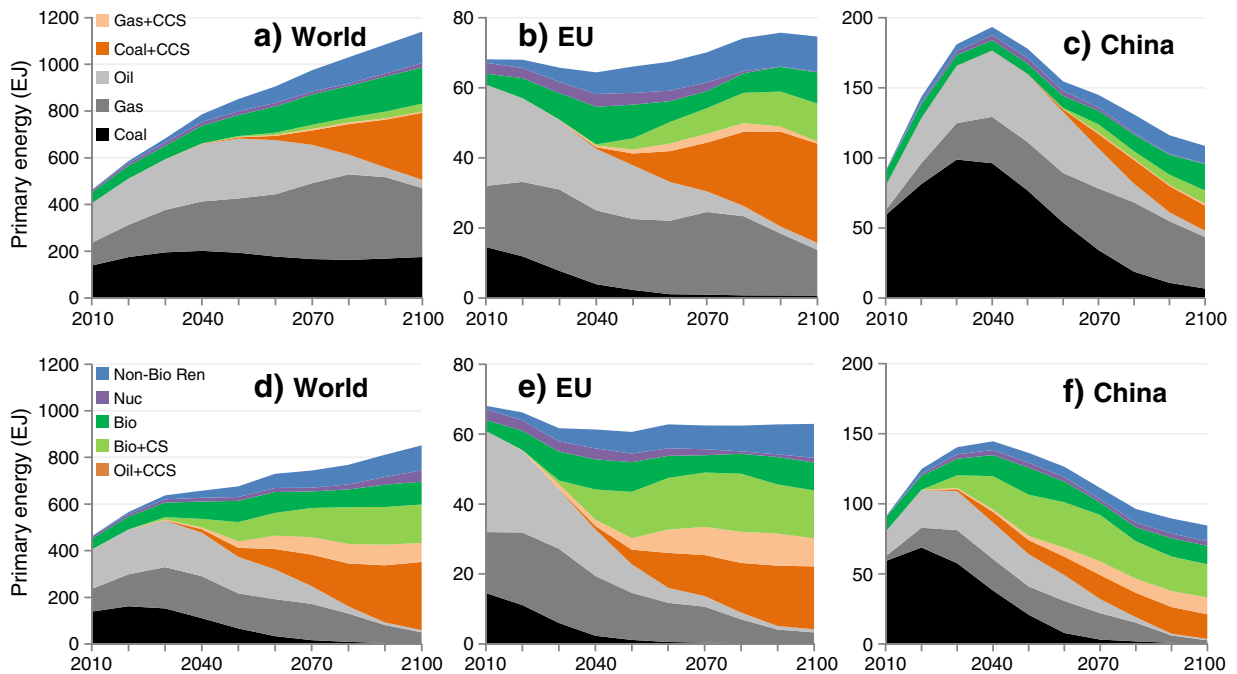


Fig. 2. Primary energy share for the world (a), EU (b) and China (c) for the RefPol and for the world (d), EU (e) and China (f) for 450P-CE scenario.

The climate policy obviously has consequences for the energy pathways. In Fig. 2, we compare the *RefPol* scenario for the world, EU and China to the 450P-CE case. In all regions, in the latter scenario unabated fossil fuel use is strongly reduced. In China and the world, the reductions take place for all fossil fuels. In the EU, coal and natural gas are already significantly reduced in the *RefPol* case – so the further reduction mainly involves oil that is replaced by biofuels in the 450P-CE case. There are two other key differences noticeable in all regions: first-of-all, there is a quite clear decrease in overall primary energy use. Secondly, in all regions there is a penetration of bio-energy in combination with CCS.

Fig. 3 shows the carbon leakage in the *RefP-CEback* scenario, i.e. the increase in emissions in the *RefP-CEback* scenario for the regions other than China and EU compared to the *RefPol* scenario. This increase results from the different leakage dynamics discussed in Section 3.2. The two channels of carbon leakage are the global energy market and land use. As shown in Fig. 3, by far the most leakage occurs via the energy market route (as a result of the fall in fossil fuel prices). We further explore these effects in Section 3.2. The small leakage via the land use channel is induced by increased bio-energy demand in the EU and China. Bio-energy demand not only affects global emissions from the land use system but also links with the energy markets (in particular, oil). This will be further explored in Section 3.3.

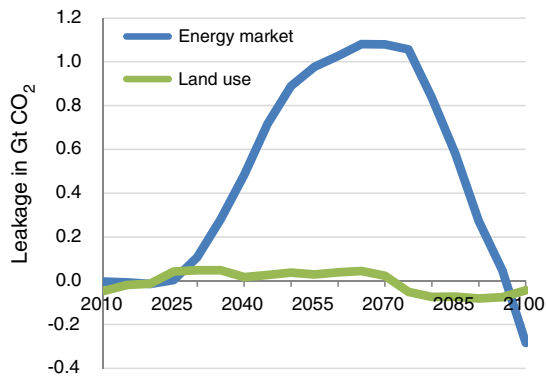
The results indicate that total (energy market + land use) CO<sub>2</sub> emissions for the rest of the world between 2010 and 2050 are about 10 Gt CO<sub>2</sub> more in *RefP-CEback* than in *RefPol*. The vast majority of it occurs via the energy market channel (90%). The IPCC [16] defines carbon leakage as “an increase in

CO<sub>2</sub> emissions outside the countries taking domestic mitigation action, divided by the reduction in the emissions of these countries.” According to this definition, between 2010 and 2050 carbon leakage in the *RefP-CEback* is ~5% (approximately 10 Gt CO<sub>2</sub> increase versus approximately 207 Gt CO<sub>2</sub> decrease). This number is relatively low compared to other studies [5,16–18] but it nonetheless emphasize that the phenomenon of carbon leakage should be taken into account considered when formulating climate policy.

### 3.2. Leakage via the energy markets

By comparison with the *RefPol* scenario, in the *RefP-CEback*, the climate policies induce a reduction of energy demand in the EU and China and a corresponding decrease in consumption of all fuel types, except for bio-energy (Fig. 4a). This effect is a result of improved efficiency and of substituting bio-energy and other renewables for oil, coal, and natural gas. For coal and gas, this decrease in consumption occurs mainly in the industry and electricity sector (indicated by “other”). For oil, this occurs not only in the electricity and non-energy sector but also in the transport sector. The decrease in energy demand results in a fall in the price of tradable fuels (except bio-fuels) on the global energy market (Fig. 4b). The impact on gas prices is smaller, reflecting the smaller decrease in consumption and the fact that markets are less connected.

A fall in the price of natural gas and oil fuels results in higher energy demand in regions outside the EU and China (Fig. 5a). In contrast, an increase of the bio-energy price in combination with the reduced fossil fuel prices reduces the use of modern bio-fuel in the transport sector outside the EU and



**Fig. 3.** Leakage, i.e. the increase in CO<sub>2</sub> emissions (outside the EU and China) in the Gt CO<sub>2</sub> of RefP-CEback scenario (versus RefPol used as reference).

China and increases bio-energy exports (Section 3.3). The electricity and industrial sector shows a similar pattern, but with an increase in coal use.

The increase in emissions occurs in different parts of the world and depends somewhat on the sectoral energy use in the different regions (in Asia and Oceania the impact on electricity and industry is the largest, while in North America the impact on transport is most noticeable)(Fig. 5b).

Most emissions come from the electricity sector (~4.9 Gt CO<sub>2</sub>, cumulative for 2010–2050) because of higher additional electricity demand and coal use, to replace bio-energy. Also the transport sector (~3.4 Gt CO<sub>2</sub>, cumulative for 2010–2050) shows strong increase in emissions as a result of the change in oil demand.

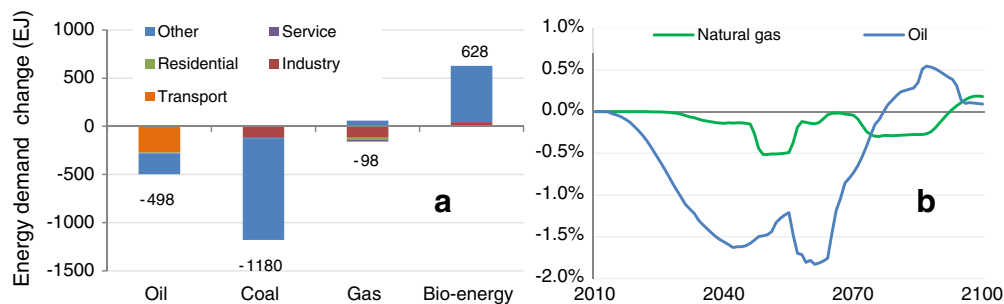
### 3.3. Leakage via land-use change

In addition to the energy sector, Fig. 3 also shows a small leakage impact in terms of land-use emissions (~1 Gt CO<sub>2</sub> in the 2010–2050 period). In this section we look more closely into the impacts of bio-energy demand and supply.

In recent years there has been an active debate in the scientific literature on the impacts of bio-energy on land-use change emissions [19,20]. In IMAGE, increased production of bio-energy crops does lead to increased emissions from land use, as shown in Fig. 6, in which cumulative production of bio-energy crops and cumulative land-use emissions are plotted for 2010–2050 (see Appendix A for a description on how this plot was derived). The land-use emissions at low levels of bio-energy production result from the land-use changes that are already included in the baseline scenario and are mostly driven by food production. The figure, however, shows that increasing bio-energy production worldwide leads to higher CO<sub>2</sub> emissions related to land use (over the range explored, the average impact increases linearly). The emissions from production of different bio-fuel crops on abandoned agricultural land are slightly higher than those from bio-fuel production on natural grassland, as abandoned land is more productive in terms of net primary production (NPP) than natural grassland.

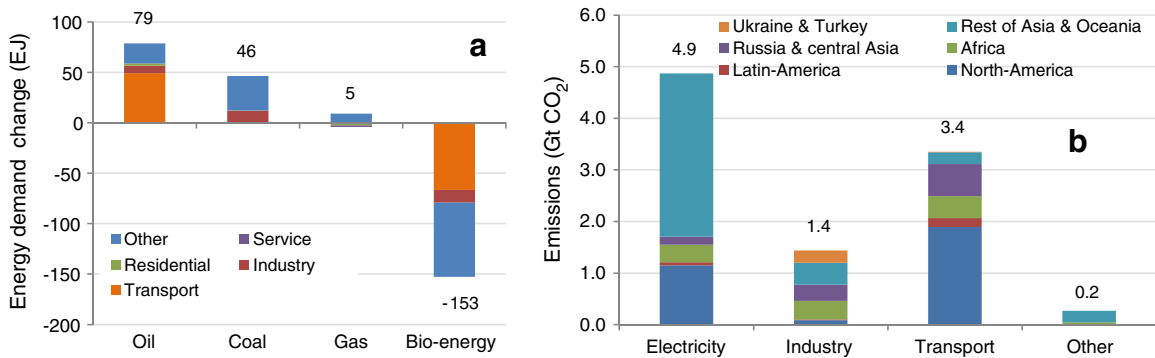
Fig. 7 shows regional bio-energy production and demand in RefPol and RefP-CEback scenarios for 2010–2050. The results show that in both scenarios the demand for bio-energy in China and the EU considerably exceeds local production (indicating that a substantial part of the bio-energy is imported). In the RefPol scenario, this is mostly a consequence of the relatively stringent policies that have been assumed for the EU and that lead to bio-energy imports. The RefP-CEback scenario results in a further increase of bio-energy demand in both the EU and China. The higher demand leads not only to some increase in production in the region concerned (China and EU by 220 EJ) but also to a big increase in imports. This import is possible due to the potential for relatively cheap bio-energy to be produced in regions elsewhere, where demand for bio-energy is low (even stimulated by the effect on oil prices noted earlier). As a result, production of bio-energy increases in all regions by 262 EJ compared to RefPol. All other regions have a surplus of bio-energy production. The higher production causes bio-energy prices in these exporting regions to rise, resulting in a slight reduction in domestic consumption.

We can estimate the potential savings by the bio-energy use in the EU and China by assuming that the additional bio-energy mostly replaces oil. In that case, increased CO<sub>2</sub> emission



**Fig. 4.** (a): Additional cumulative primary energy demand per sectoral fuel use in the period 2010–2050 for EU and China: comparison between RefP-CEback and RefPol scenarios. The sector “other” covers the electricity and hydrogen sector, of which electricity is the largest. (b): Relative difference of the weighted (by consumption level) average oil and natural gas price in \$/gigajoule (GJ) for all regions outside the EU and China in the period 2010–2100: comparison between RefP-CEback and RefPol scenarios.





**Fig. 5.** (a): Additional cumulative primary energy demand per sectoral fuel use in the period 2010–2050 in the rest of the world (outside the EU and China): comparison between RefP-CEback and RefPol scenarios. The “other” sector covers the electricity, non-energy and hydrogen sector, of which electricity is the largest. (b): Sectoral difference in cumulative emissions in 2010–2050: comparison between RefPol and RefP-CEback in the rest of the world (“other” comprises bunker oil, hydrogen, non-energy, residential and service sectors).

associated with bio-fuel crops in both China and EU and the other regions is about 2.2% of the carbon saved.

The effect of climate policy in the EU and China is particularly marked in the Russian and Central Asian region, with a production increase by more than 200% as compared to the RefPol scenario. This region has a relatively high potential to produce bio-energy from abandoned agricultural land and natural grasslands. In contrast, in most tropical regions the area required for food production increases, limiting the scope for rapid expansion of crops grown for bio-fuel.

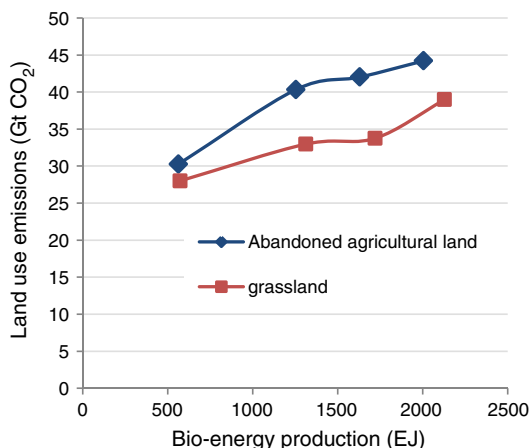
Growing bio-fuel crops on abandoned agricultural land implies that the forest regrowth that would normally happen in absence of this activity is precluded. Hence emissions will rise by comparison with the reference case. Moreover, in the case of natural grassland, some existing natural biomass cover

is removed. We expect that land-use CO<sub>2</sub> emissions that result from bio-fuel crop expansion depend on the vegetation of the area used for growing these crops, which, in turn, is dependent on geography and local climate [21]. This implies that the relationship between bio-energy production and energy supply (shown globally in Fig. 7) is also region-dependent. Whereas Russia and Central Asia show a strong increase in bio-energy production, the increase in land-use emissions is relatively small because the reference natural vegetation is grassland. In tropical regions, the reference vegetation (rainforest) is more carbon-intensive, and therefore bio-energy production is likely to result in more CO<sub>2</sub> emissions from land use [22]. Nevertheless, the specific details of the land use interactions require further investigation.

### 3.4. Discussion

The IMAGE model estimates that total leakage for the 2010–2050 period will be about 10 Gt CO<sub>2</sub>. These results are within the range found in the AMPERE study [17]. This study looked into carbon leakage effects of the fossil fuel markets for the period 2010–2030 by means of different models (10) and found large range of results from –0.1 to 47.8 Gt CO<sub>2</sub>. Interestingly, the IMAGE leakage rate increases over time and is still quite small in the period up to 2030. This has two reasons; first, the price differences in IMAGE, induced by the domestic climate policies, are a result of depletion dynamics (less fossil fuel consumption), an effect that only becomes apparent over time. Secondly, IMAGE includes (technological) inertia which implies that the model cannot directly respond to the price differences. Therefore, in this paper we take a longer time frame (2010–2050) and include emissions from land use. In this period we find a higher leakage rate of ~5% (10 Gt CO<sub>2</sub>, see Section 3.1).

Three aspects suggest that our estimates are conservative even on the longer term. First, in IMAGE, the impact of leakage is only covered by long-term dynamics: short-term impacts (such as oil price reductions resulting from under-exploitation of existing capital) are not included in the model. Secondly, the relocation of energy intensive industries is not captured in the



**Fig. 6.** Cumulative bio-energy production versus land-use emissions (2010–2050) when production is increased on abandoned agricultural land (blue) and grassland (red), starting from baseline scenario values.

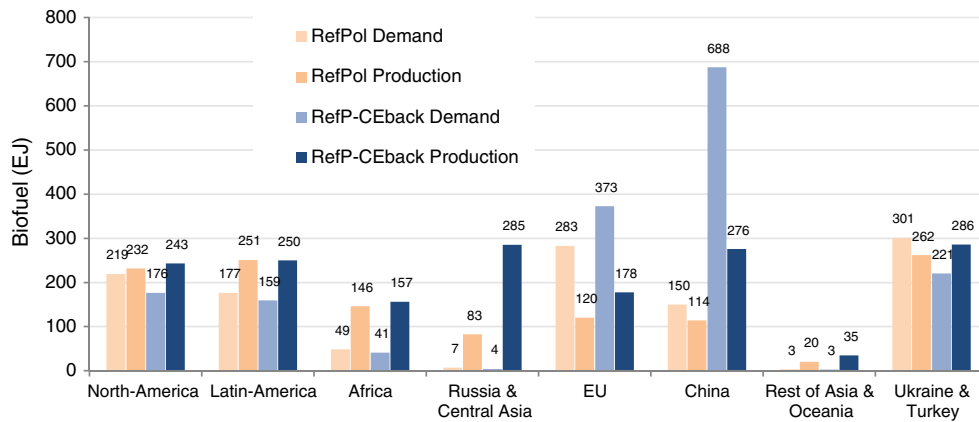


Fig. 7. Cumulative regional bio-energy production and demand for 2010–2050 for scenarios RefPol and RefP-CEback.

analysis and thirdly, we assume that all bio-energy production is subject to sustainability criteria and occurs only on abandoned agricultural land or natural grassland. However, in practice, this is not necessary the case, resulting potentially in more LUC emissions than anticipated [20,23].

Several of the scenarios explored in this paper change course after 20 years. However, the policies continue to affect energy production and emissions for 30–40 years after they are abandoned. Also this results from inertia. An important reason for the inertia is the lifetime of capital: for example, bio-energy power plants have a lifetime of 30–40 years. The investment tied up in the transport sector will cause global oil consumption to be lower until around 2060, as bio-fuel production continues. However, this decrease is offset by oil consumption increasing at a later date in response to lower oil prices. In the natural system, emissions emitted (or avoided) in the next 30 years will lead to a higher (or lower) average CO<sub>2</sub> concentration for the 21st century.

Many papers have explored the potential impact of bio-energy use on emissions related to land use [20,24–26]. The calculations we have presented confirm the importance of such land use change related emissions. In the scenarios we have explored, the demand for bio-energy in EU and China surpasses domestic production significantly and therefore both regions must import bio-energy from other regions (and in much greater amounts than is the case in uniform policy scenarios, because demand is lower in exporting regions). In exporting regions, demand decreases (as a result of the price increase) and production rises. The decrease actually somewhat offsets the potential leakage impacts.

#### 4. Conclusions

The international community has agreed to the objective of limiting the average global temperature increase to a maximum of 2 °C compared to pre-industrial levels by the end of the 21st century. Although an optimal economically efficient response would probably be one that is global and coordinated, the current approach to global climate policy consists of voluntary pledges. As a result, the efficacy of this climate policy depends on individual country ambitions. In such a

situation, leakage of CO<sub>2</sub> could play a role. In this paper, we investigate this using the IMAGE model.

Fragmented climate policy with first movers could lead to carbon leakage from the energy system to land use through bio-energy demand. If only long-term dynamics are taken into account, the impacts are around 5% of the emissions avoided.

The vast majority of the total leakage found with IMAGE (about 90%) will occur via the energy market channel; the remaining 10% will occur through land use. Our finding that total leakage is about 5% of the emissions avoided in the region taking action suggests that the impact of land use change is limited.

The leakage impacts in the energy sectors are found to be strongest in the power and transport sectors.

The decrease in demand for fossil fuels in the EU and China results in a fall of the price of fossil fuels on the global market. A fall of the price of fossil fuels causes demand in regions outside the EU and China to rise. In contrast, the increased bio-energy price increases bio-energy exports in regions outside the EU and China reducing domestic demand. The level of fuel demand depends on sectoral energy use in different regions. The change in oil demand is particularly seen in the transport sector, with a noticeable impact in North America. Additional demand for coal comes mainly from the electricity sector (replacing bio-energy), which is particularly seen in Asia and Oceania.

An increase in production of bio-energy may lead to an increase of CO<sub>2</sub> emissions related to land use.

It is difficult to prevent the “leakage” impacts in both the energy system and the land-use system. In the case of land use in particular, an increase in bio-energy production will result in more CO<sub>2</sub> emissions related to land use, both in scenarios that are based on a global response as well as in fragmented policy scenarios [24]. It should be noted that the increase in land use emissions is mostly temporary, whereas the gains in reduced fossil emissions increase over time.

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### Appendix A. Methodology used to analyze the relation between bio-energy production and land use emissions

One possible route of emissions is via the impact of bio-energy on land use. For this purpose, we introduce a set of model experiments that examine the relationship between bio-energy and land-use emissions in IMAGE. In IMAGE, bio-energy can be produced on abandoned agricultural land and on natural grassland. Forests, nature reserves, non-productive land and urban land are assumed to be excluded (representing a situation where so-called sustainability criteria are successfully introduced). Using forest areas for bio-energy production would usually be counterproductive, given the carbon consequences. Not only do the sustainability criteria constrain bio-energy, but they also diminish the indirect impacts (such as converting other land to forest). We assume that the world will indeed evolve in this direction,

but this is by no means certain. It will require sustainability criteria for bio-energy production and other forms of land-use to be enforced worldwide. This might be achieved by ensuring that deforestation emissions are properly accounted for in the UNFCCC, or by more stringent national land-use policies.

In order to explore the relationship between bio-energy use and land-use emissions, we ran a set of scenarios in which the deployment of bio-energy production was increased for all regions, from the low production levels included in the baseline scenarios, to levels near the maximum potential in IMAGE (i.e. 10%, 50%, 70% and 90% of the maximum potential). These experiments were run separately for abandoned agricultural land and natural grassland (thus in total 8 model runs). Whereas on natural grassland the production of bio-energy does lead to CO<sub>2</sub> emissions because the natural vegetation is removed before bio-energy production can commence, on abandoned agricultural land bio-energy production also leads to net emissions compared to the baseline, because if the land had not been brought into use for bio-fuel production, the natural vegetation would have returned.

### Appendix B. Targets in reference policy scenario for IMAGE regions [10]

Region	GHG emissions reduction in 2020 <sup>a</sup>	GHG2 intensity reduction in 2020 <sup>b</sup>	Modern renewable share in electricity <sup>c</sup>	Installed renewable capacity in 2020 <sup>d</sup> (wind, solar)	Installed nuclear power capacity <sup>d</sup>	Average GHG emissions intensity reduction after 2020 <sup>e</sup>
BRA	– 18% (BAU)					2.7%
CAN	– 5% (2005)		13% (2020)			2.4%
CEU	– 15% (2005)		20% (2020)			3%
CHN		– 40%	25% (2020)	200 GW; 50 GW	41 GW (2020)	3.3%
EAF						2.3%
INDIA		– 20%		20 GW; 10 GW	20 GW (2020)	3.3%
INDO	– 13% (BAU)		7.5% (2025)			2.1%
JAP	– 1% (2005)			5 GW; 28 GW		2.2%
KOR	– 15% (BAU)			8 GW; –		3.3%
ME						1.5%
MEX	– 15% (BAU)		17% (2020)			2.8%
NAF						1.5%
OCE	– 13% (2005)		10% (2020)			3%
RCAM	– 15% (BAU)					2.1%
RSAF						2.3%
RSAM	– 15% (BAU)					2.1%
RSAS						2.9%
RUS	+ 27% (2005)		4.5% (2020)		34 GW (2030)	2.6%
SAF	– 17% (BAU)					2.8%
SEAS			15% (2020)			2.1%
STAN						2.6%
TUR				20 GW; –		2.3%
UKR						2.6%
USA	– 5% (2005)		13% (2020)			2.5%
WAF						2.3%
WEU	– 14.7% (2005)		20% (2020)			3%

<sup>a</sup>Including land-use change, land-use change and forestry (LULUCF) and relative to 2005 or business as usual (BAU) as specified in brackets. (If GHG emissions in baseline is lower, baseline trajectory is adopted for the region concerned.)

<sup>b</sup>Including LULUCF and relative to 2005. (If GHG intensity reduction in baseline is higher, baseline trajectory is adopted for the region concerned.)

<sup>c</sup>Reference quantity is always electricity production except for EU27 where it is final energy.

<sup>d</sup>Capacity targets are minimum targets; target year is specified in brackets.

<sup>e</sup>%/year; GHG intensity improvement rates calculated based on Kyoto GHG equivalent emissions including LULUCF relative to GDP. (If GHG emission (intensity) reduction in baseline is higher, baseline trajectory is adopted for the region and period concerned.)



**Abbreviations**

BRA = Brazil	ME = Middle East	SAF = South Africa
CAN = Canada	MEX = Mexico	SEAS = Southeast Asia
CEU = Central Europe	NAF = North Africa	STAN = Kazakhstan region
CHN = China	OCE = Oceania	TUR = Turkey
EAF = East Africa	RCAM = Rest of Central America	UKR = Ukraine, Belarus, Moldova
INDIA = India	RSAF = Rest of Sub-Saharan Africa	USA = United States of America
INDO = Indonesia	RSAM = Rest of South America	WAF = West Africa
JAP = Japan	RSAS = Rest of South Asia	WEU = Western Europe
KOR = Korea	RUS = Russia	

**Appendix C. Definition aggregated regions in Figs. 5b and 7**

Africa	China	EU	North-America	Rest of Asia & Oceania	Russia and Central Asia	Latin America	Ukraine & Turkey
EAF	CHN	CEU	CAN	INDIA	ME	BRA	TUR
NAF		WEU	MEX	INDO	RUS	RCAM	UKR
RSAF			USA	JAP	STAN	RSAM	
SAF				KOR			
WAF				OCE			
				RSAS			
				SEAS			

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