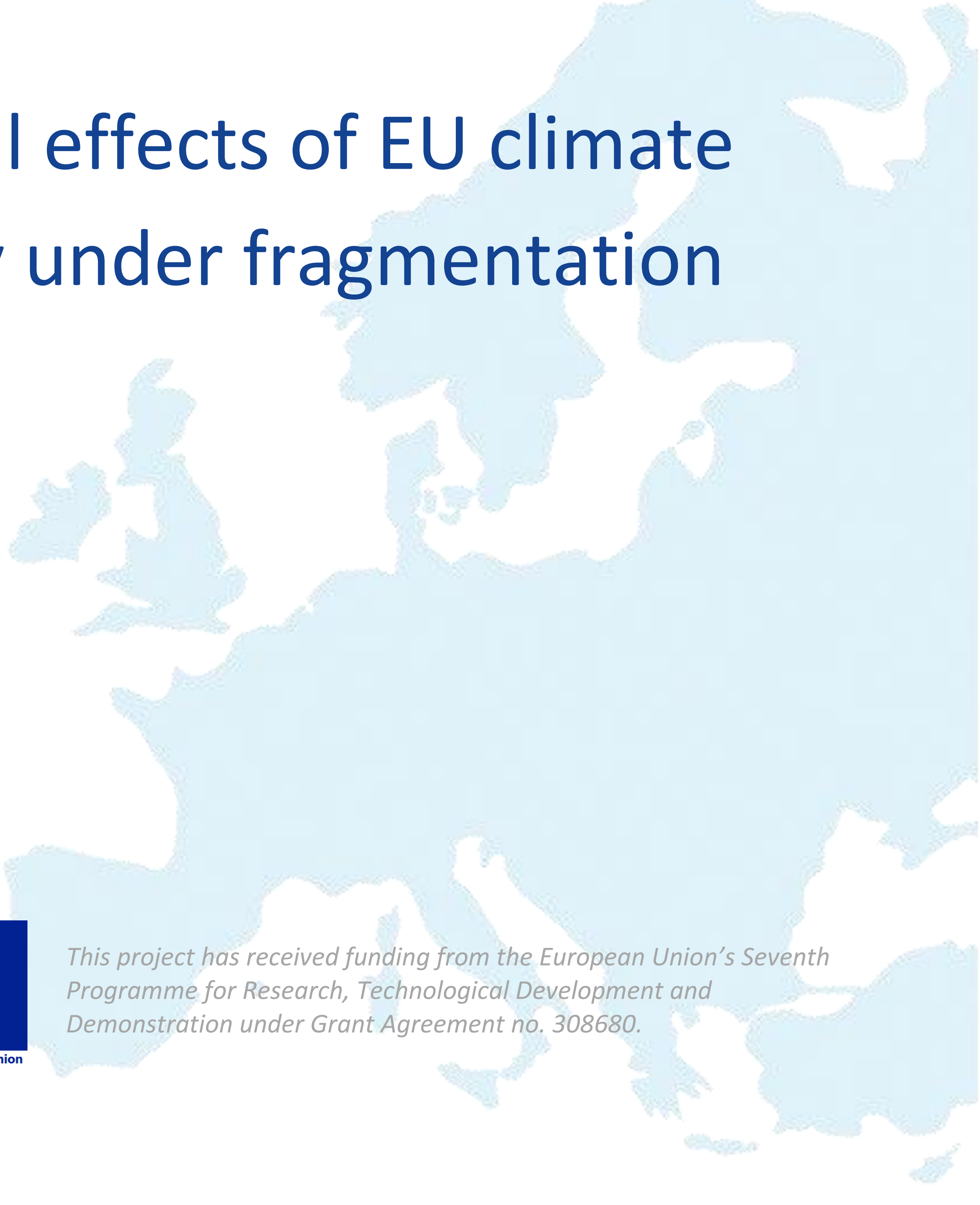
CECILIA 2050

OPTIMAL EU CLIMATE POLICY

Choosing Efficient Combinations of Policy Instruments for Low-carbon development and Innovation to Achieve Europe's 2050 climate targets

Global effects of EU climate policy under fragmentation



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1 Executive summary

This report examines the implications of a range of possible agreements for the reduction of greenhouse gases (GHGs) from industrial and terrestrial sources in terms of the likely future temperature increase, mitigation costs by region and a number of other important indicators. The agreements considered range from, at one extreme, the case where the EU goes alone for a target reduction of 80% by 2050 (FR1), to, at the other extreme, a world in which most of the countries participate. In between it considers scenarios involving only the EU and US with an 80% reduction target (FR2), all developed countries committing to the 80% target (FR3), all developed countries and China committing to the target of start reducing their emissions in 2030 (FR4), all developed countries plus Brazil, South Africa, India and China (BASIC) committing to the same target (FR5) and all countries in the world, except Africa, Russia and the Middle East committing to the same target (FR6). In all cases where the 80% target is imposed it applies to the region as a whole. In each case the results are compared relative to a baseline scenario in which no further measures are taken to reduce GHGs.

The tool used for the analysis is GCAM, a dynamic recursive economic partial equilibrium model driven by assumptions about population size and labour productivity that determines gross domestic production (GDP) in 32 geopolitical regions operating on 5-year time steps from 1990 to 2100. The model tracks emissions and atmospheric concentrations of GHGs, carbonaceous aerosols, sulphur dioxide, and reactive gases and provides estimates of the associated climate impacts. An important feature of the GCAM architecture is the terrestrial carbon cycle model embedded within the agriculture-land-use system model. Thus, all land uses and land covers, including the non-commercial lands, are fully integrated into the economic modelling in GCAM. This coverage gives GCAM the capability to model policies that jointly cover carbon in all activities in the energy, agriculture, forest, and other land uses. The economic tool in the model is a carbon tax that applies equally to industrial and terrestrial emissions (UCT, or universal carbon tax), but with two different carbon markets as the objectives for developing and developed regions differ although they are converging in emission per capita in 2100.

One of the key impacts of the different scenario is carbon leakage: the move of sources of emissions outside a region that has restrictions on them to a region that does not. In this study two sources of leakage are considered: one due to the different fuel prices in countries with a carbon target as opposed to countries without one (referred to as industrial carbon leakage or ICL), and the other resulting from a shift of biomass/food production that is carbon intensive out of regions with a carbon target to regions without one (referred to as terrestrial carbon leakage or TCL). The analysis shows the total leakage rates to significant, starting at around 20% with FR1 and FR2 and falling to 6% with FR6. In the period to 2050 TCL is the dominant form of leakage but in the period 2050-2100 it is ICL that dominates. The conclusion emerges that it is important to include TCL in the model, certainly for the medium term to understand leakage effects.

The second important conclusion from the study relates to emissions of GHGs and associated temperature changes. Reductions in global emissions are ameliorated by carbon leakage. This is especially true for the scenarios where the developing countries do not participate (FR1, FR2, FR3) but also in the case of China joining to the coalition. In 2050 the emissions of non-participating countries is quite a lot higher that the project in the reference scenario. The implications for temperature are therefore clear: with the baseline it increases to 3.8°C above preindustrial levels by 2100 and with FR1, FR2 and FR3 the increases are, respectively, 3.7, 3.5 and 3.4°C. So a very small benefit is obtained from such agreements in terms of a lower temperature increase. Even with FR6 we end up with an increase of 2.4°C, thus missing the 2°C target. It needs a global agreement to get to that target or a greater effort of the rest of countries.

The third conclusion relates to the policy costs of the different scenarios. As expected the costs rise with the inclusion of more countries into the agreement (the other side of that coin is that we get benefits in terms of less emissions and smaller temperature increases). The costs to any one region may rise when the agreement is widened to include more countries, or it may fall (which happens in a few cases only). Total costs as a percent of world GDP go up from 0.13% with FR1 to 2.5% with FR6. This question of the distribution of costs is important and not fully analysed in this report. It needs further work, comparing the benefits of the wider agreements against the costs and finding ways to share the benefits.

The report looks specifically at the implications of the analysis for the EU in some detail. First it is clear that FR1 (going it alone) makes virtually no impact on temperature reduction. This is partly due to the relatively small share of world emissions but also to the major leakage effect we observe in the model. Second is the response of primary energy consumption responds to fragmented climate regimes. The most important effect can be found in coal, which declines increasingly with each widening of the fragmented regime. Another important effect is the increased presence of biomass in the energy mix, which grows from 8.2 EJ/year in REF scenario to 18.6 EJ in FR1 and 14.4 in FR6. However, the increase in demand for biomass is not coupled with an increase of biomass production in the EU. The system gives incentives to store carbon in EU's land through afforestation and to reduce the land devoted to crop and biomass production. The study shows that the area devoted to crop and biomass production decreases by 36% and 38% in FR1, respectively, and 17% and 18% in FR6. Therefore, EU climate policies affect not only energy and industry but also the agro-food systems.

Finally the report notes some important caveats. First, this report has examined an idealized carbon tax international policy architecture and not discussed the difficulties associated with the implementation such taxes on terrestrial emissions. Second, part of the results rely on the assumption that CCS technology will be commercially available by 2020, which, according to recent studies is a very optimistic assumption. Third, our results on land use are very dependent on assumed exogenous crop productivity improvements. Fourth, the effect of climate on yields is not included. This is one of the improvements in the modelling approach currently being discussed by the IAM and GCAM community.

2 Introduction

The objective of stabilizing climate “at a level that would prevent dangerous anthropogenic interference with the climate system” (UNFCCC 1992) has been translated into the long-held target of limiting global average temperature rise to 2 degrees Celsius (°C) above the pre-industrial level. According to the Intergovernmental Panel on Climate Change (IPCC 2013), the 2°C objective will require atmospheric concentrations of greenhouse gases (GHG) to remain well below 450 ppm CO2-equivalent, which in turn will require global GHG emissions to peak before 2025 and then fall by up to 50 % by 2050 compared to 1990 levels.

Global climate change constitutes one of the greatest collective action problems in human history. Because GHGs mix uniformly in the upper atmosphere, damages are completely independent of the location of emissions sources. Thus, a multi-national response is required. To address effectively the risks of climate change, efforts that engage most countries (at least the “major emitters”) will need to be undertaken. The Kyoto Protocol (UN 1998), a first attempt by the international community to curb GHG emissions through a legally binding international agreement, did not achieve a decisive breakthrough in international climate policy (Prins et al. 2010) but it has taught policy-makers some valuable lessons and possibly laid the groundwork for more ambitious efforts (Schiermeier, 2012). One of the lessons learned from the Kyoto Protocol is that a fragmented climate regime may pave the way for a universal regime in the long run (Hof et al. 2009). Consequently, the United Nations Framework Convention on Climate Change (UNFCCC) process has experienced a shift from a top-down legally binding climate policy architecture towards a bottom-up approach in which countries decide individually on emission reduction targets (the so-called “voluntary pledges”).

At the Conference of Parties held in Warsaw in November 2013 (COP 19), by its decision 1/CP.19, all Parties were invited to initiate or intensify domestic preparations for their intended nationally determined contributions (INDCs) towards the achievement of the climate stabilization objective. INDCs are to be communicated well in advance of COP 21 in Paris (December 2015) and by the first quarter of 2015 by those Parties ready to do so. It is hoped that the 2015 Agreement will spur the efforts of the international community to achieve the goals of the UNFCCC to prevent dangerous climate change, and will replace from 2020 onwards the Kyoto Protocol.

The EU was one of the first regions to reach an internal decision on an INDC target. It agreed on 23 October 2014 the domestic GHG reduction target of at least 40% compared to 1990 levels and a target of at least 27% for renewable energy and energy savings by 2030. Few weeks later, on 12 November 2014, China and the United States of America (US) jointly announced their respective post-2020 actions on climate change. According to the Joint-Agreement, the US intends to achieve an economy-wide target of reducing its emissions by

26%-28% below its 2005 level in 2025 and China intends to achieve the peaking of CO2 emissions around 2030 and increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030. Therefore, it is expected that climate action will remain fragmented for a long time with a variety of regional/national climate policy agendas being pursued in different parts of the world.

One of the main concerns about fragmented climate regimes is carbon leakage. A fragmented climate regime is characterized by unequal carbon prices across regions and sectors and this may lead to relocation of production to regions with less stringent mitigation rules, leading to higher emissions in those regions and, therefore, to carbon leakage. Until very recently the main focus of the carbon leakage literature has been "industrial" carbon leakage (ICL). Calvin et al. (2009) offer a thorough discussion and quantification of the three different channels (energy market, competitiveness and advancement of low-carbon technology) by which carbon price differentials lead to changes in carbon emissions outside the regions taking domestic mitigation action. Antimiani et al 2013 provides alternative policy measures aimed at reducing carbon leakage

But there is another potential channel for carbon leakage that has received little attention so far: the carbon leakage triggered by land use changes, which we will refer to as "terrestrial" carbon leakage (TCL). TCL can arise, for instance, when a regional carbon tax is applied not only to industrial but also to terrestrial carbon emissions and, as a consequence, market forces drive these regions to re-locate the production of food and/or bioenergy to regions with less stringent terrestrial carbon mitigation rules. Wise et al. (2009), Calvin et al. (2010), Calvin et al. (2014), Kuik (2014) and Otto et al. (2015) constitute examples of an emerging subset of the literature focusing on the TCL associated to carbon mitigation policies. However, to the best of our knowledge, no previous study has carried out a comparison of the magnitudes of the two forms of leakage (ICL and TCL). This report will contribute to fill that gap. Moreover, and although we will analyse fragmentation in general, we will also focus our attention to the implication for the EU.

The report is organized as follows. Section 3 provides an overview of the GCAM model with a focus on those aspects that are of particular interest for the analysis. Section 4 lays out an overview of the design and the different scenarios of fragmented climate regimes considered in the report. Section 5 discusses the key findings of the study in terms of environmental effectiveness (sub-section 5.1), effects on energy systems (sub-section 5.2), effects on land use (sub-section 5.3), effects on climate (sub-section 5.4) and effects on mitigation costs (sub-section 5.5). Section 6 explores the main implications of the analysis for the European Union. Finally, section 7 draws conclusions.

3 Methodology

3.1. Overview

The analysis in this report uses the Global Change Assessment Model (GCAM), an integrated assessment model that links the world's energy, agriculture and land use systems with a climate model. GCAM, that traces its origin to a model developed by Edmonds and Really (1985) and was previously known as MiniCAM (see Edmonds et al. 1997), is a community model developed and run at the Joint Global Change Research Institute, University of Maryland1. GCAM was one of the four models chosen by the Intergovernmental Panel on Climate Change (IPCC) to create the Representative Concentration Pathways (RCPs) for the IPCC's fifth Assessment Report (see Thomson et al. 2011).

GCAM is a dynamic recursive economic partial equilibrium[2] model driven by assumptions about population size and labor productivity that determines gross domestic production (GDP) in 32 geopolitical regions (see Table A1 in the Appendix) operating on 5-year time steps from 1990 to 21003. The model can be run with any combination of climate and non-climate policies in relation to a reference scenario and proved carbon price and mitigation costs. GCAM tracks emissions and atmospheric concentrations of GHGs, carbonaceous aerosols, sulfur dioxide, and reactive gases and provides estimates of the associated climate impacts. An important feature of the GCAM architecture is that the GCAM terrestrial carbon cycle model is embedded within the agriculture-land-use system model. Thus, all land uses and land covers, including the non-commercial lands, are fully integrated into the economic modeling in GCAM. This coverage gives GCAM the capability to model policies that jointly cover carbon in all activities in the energy, agriculture, forest, and other land uses.

3.2. The energy and land use systems

GCAM contains detailed representations of technology options for each of its economic components with technology choice determined by market probabilistic competition (Clarke and Edmonds 1993). The model produces outputs that include energy and agricultural prices and land use allocation. The model can track not only fossil fuel and industrial (FFI) emissions but also emissions associated to land use change (LUC).

The GCAM energy system includes primary energy resource production, energy transformation to final fuels, and the use of final energy forms to deliver energy services

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[1] Detailed information can be found at http://www.globalchange.umd.edu/models/gcam/

[2] GCAM establishes market-clearing prices for all energy, agriculture and land markets simultaneously but has no explicit markets for labor and capital and there are no constraints such as balance of payments.

[3] We work with its last version (GCAM 4.0) released in October 2014.

such as passenger kilometers in transport or space conditioning for buildings. GCAM distinguishes between two different types of resources: depletable and renewable. Depletable resources include fossil fuels and uranium; renewable resources include wind, geothermal energy, municipal and industrial waste (for waste-to-energy), and rooftop areas for solar photovoltaic equipment. All resources are characterized by cumulative supply curves, i.e. upward-sloping supply-cost curves that represent the idea that the marginal cost of resource utilization increases with deployment. Carbon capture and storage (CCS) technology is available for application to large, point-source emission facilities. These include electric power generation, hydrogen production, cement manufacturing and large industrial facilities. A complete documentation of all the technologies in the energy system is provided in Clarke et al. (2009).

The agriculture and land use component[4] is fully integrated into (i.e. solved simultaneously with) the GCAM economic and energy system components. Data for the agriculture and land use parts of the model comprises 151 sub-regions in terms of land use, based on a division of the extant agro-ecological zones (AEZs). Land is allocated between the various uses based on expected profitability, which in turn depends on the productivity of the land-based product (e.g. mass of harvestable product per ha), product price, and non-land costs of production (labor, fertilizer, etc.). The productivity of land-based products is subject to change over time based on future estimates of crop productivity change. This increase in productivity is exogenously set, adopted from projections from FAO (Bruinsma 2003). GCAM includes several different commercial and non-commercial land uses including ten crop categories[5], six animal categories[6], three bioenergy categories (described below), forests, pasture, grassland, shrubs, desert, tundra, and urban land. All agricultural crops, other land products, and animal products are globally traded within GCAM.

Bioenergy in GCAM is classified into three categories: traditional bioenergy, bioenergy from waste products, and purpose-grown bioenergy. Traditional bioenergy comprises straw, dung, fuel wood and other energy forms that are utilized in an unrefined state in the traditional sector of an economy. Traditional bioenergy use, although significant in developing nations, is a relatively small component of global energy and, as regional incomes increase over the century, it becomes less economically competitive. Bioenergy from waste products, is a by-product of another activity. The amount of potential waste that is converted to bioenergy is based on the price of bioenergy. However, the bioenergy price does not affect production of the crop from which the waste is derived. Purpose-grown bioenergy refers to crops whose primary purpose is the provision of energy. The amount produced of this category depends on the profitability with respect to other land-use

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[4] A full description of the agriculture and land use module in GCAM can be found in Kyle (2011) and Wise and Calvin (2011).

[5] The ten crop categories are Corn, Rice, Wheat, Other Grains, Sugar, Root Tuber, Palm Fruit, Fiber Crops, Oil Crops and Other Crops.

[6] The six animal product categories are Beef, Dairy, Pork, Poultry, Sheep, Goat and Others.

options. The productivity of those crops is based on region-specific climate and soil characteristics and varies by a factor of around three across the GCAM regions. GCAM considers also the possibility of using bioenergy in the production of electric power and in combination with CCS technologies.

4 Scenarios

In this section we present the scenarios used in this report. As it was mentioned in the introductory section, the UNFCCC process has experienced a shift from a top-down legally binding climate policy architecture towards a bottom-up approach and all Parties have been invited to decide their INDCs towards the achievement of the climate stabilization objective. In this context, it is the EU that has most clearly expressed its ambition by aiming for an emission reduction by 80% by 2050 and to consider action even if international agreement is not reached[7]. China's long term commitment is less clear, but it has announced the commitment to "achieve the peaking of CO2 emissions around 2030". With regard to the rest of the Parties, the variety of domestic situations each country faces in reducing emissions leads us to expect also a wide diversity of INDCs. However, the details of most of the remaining INDCs will not be released before the end of 2015. Consequently, in this report we will assume that the regions from the developed world that decide to take part in the international climate regime will follow EU´s commitments (reduce emissions by 80% in 2050) and the regions from the developing world that decide to take part in the international climate regime will follow China´s commitments (peak emission in 2030)[8].

With respect to long-term climate policy, we assume that, despite its fragmentation, the international climate regime will be guided by the principles provided by the "common but differentiated convergence" (CDC) approach suggested by Höhne et al. (2006) and this will mean that per capita emissions will have to converge to an equal per-capita emissions level[9] in 2100.

Table 1 presents the scenarios we use for our analysis. In the reference scenario (REF) we look at the possible development of GHG emissions in the absence of climate policies. The

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[7] The US announced on 12 November 2014 that would reduce its annual emission of GHGs "by 26-28 percent below its 2005 level in 2005 and to make best efforts to reduce its emissions by 28 percent". This is not as clear as the EU's announcement but it seems to be consistent with the pledge made by the US Government in 2010 to reduce annual emissions by 83 percent by 2050 compared with 2005.

[8] Table A.1 in the appendix provides the classification of countries in developed/developing regions used in this report.

[9] The convergence level will be set at 0.5 tons of CO2-e, the maximum per-capita emission level that would be required in GCAM to meet the 2°C stabilization target if every region in the world would cooperate under a uniform climate regime.

six other scenarios (scenarios FR1-FR6) consider different possibilities of engagement of regions in the international climate regime. In choosing the groups of regions that take part in these scenarios of fragmented climate action we assume that all or part of the regions in the developed world may consider engaging in climate action even if developing regions do not engage, that some regions in the developing world will engage in climate action only if developed regions also engage in climate action and that some regions, for reasons which may include poverty or high dependency of their economies on fossil fuel resources, will never engage in climate action.

Table 1. Scenarios

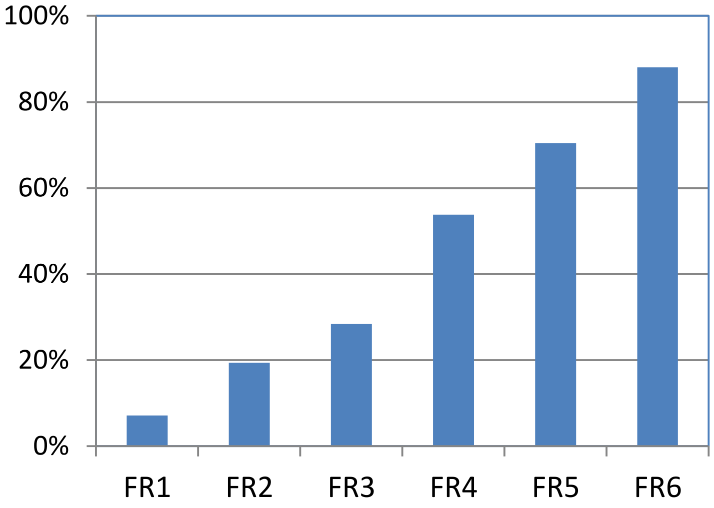
Scenarios	Participating Regions
REF	None
FR1	EU-27
FR2	EU-27 + US
FR3	Developed
FR4	Developed + China
FR5	Developed + BASIC
FR6	All countries, except Africa + Russia + Middle East
FRS	All

Note: The BASIC (Brazil, South Africa, India and China) group was formed by an agreement on 28 November 2009. The four committed to act jointly at the Copenhagen climate summit. The list of countries classified as developed and developing can be found in Table A1 in the Appendix. In FR6, South Africa is excluded from Africa.

Figure 2 shows the share of the global CO2 emissions covered by each of the fragmented scenarios in 2050. If only the developed regions take part in the international climate regime, the share ranges from 7% (FR1) to 28% (FR3). If developing regions take part, the share ranges from 54% (FR4) to 88% (FR6).

All the scenarios apply a Universal Carbon Tax (UCT) in the participating regions. This means that both industrial and terrestrial emissions have the same carbon tax. Wise et al. (2009) shows that if only industrial emissions are taxed the production of biomass would be very high (>300EJ/year) and that could compromise many ecosystem services.

Figure 1. Share of the global total CO2 emissions by scenario, 2050



5 Global results

5.1 Environmental effectiveness: carbon leakage and emissions

Let us first clarify that this report will focus on two types of carbon leakage effects: ICL and TCL. With regard to ICL, we have already mentioned in the introductory section that carbon price differentials lead to changes in industrial carbon emissions through different channels among which the three most important are: (1) the fossil fuel price channel, where reduction in global energy prices due to reduced energy demand in climate-constrained regions triggers higher energy demand and CO2 emissions; (2) the competitiveness channel, where carbon-constrained industrial products lose international market shares to the benefit of unconstrained competitors; and (3) the technology-diffusion channel, where carbon-saving technological innovations induced by climate policy in climate-constrained regions spill over to regions with less stringent climate policy. Incorporating the complex mechanisms that drive international migration of industries and diffusion of technologies in integrated assessment models such as GCAM is a very difficult task. Therefore, in this report we will focus exclusively on the fuel price channel when measuring ICL.

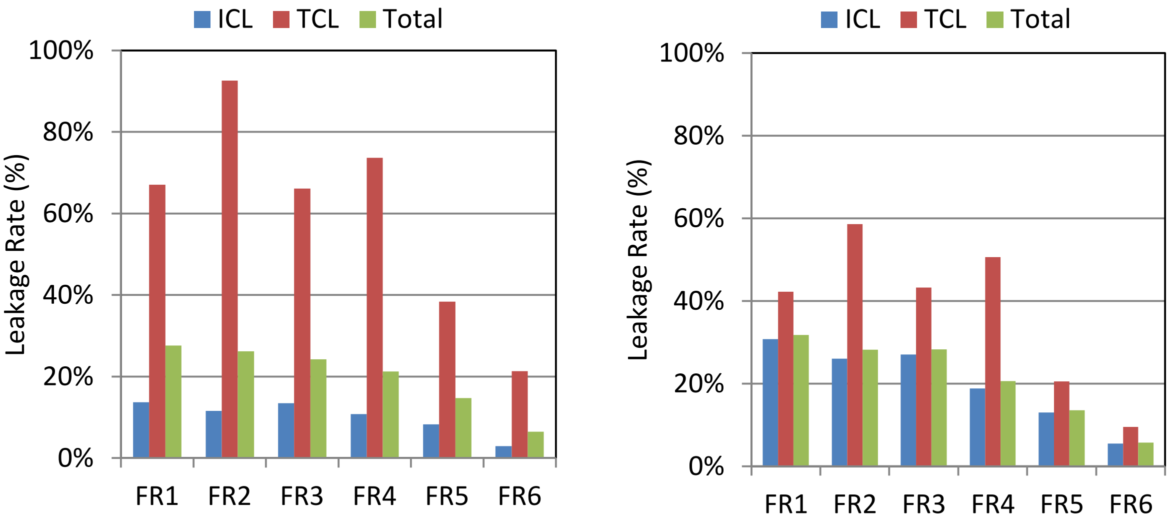
Having clarified this aspect, we will now present the key findings of the study with regard to the carbon leakage associated to fragmented climate policy action. Barker et al. (2007) define the carbon leakage rate as the increase in CO2 emissions outside the regions taking domestic mitigation action divided by the reduction in the emissions of these regions. Thus, if we represent the emissions in participating and non-participating regions in the FRX fragmented climate regime as E_{P}^{FRX} and E_{NP}^{FRX}, respectively, and the emissions in participating and non-participating regions in the reference scenario as E_{P}^{REF} and E_{NP}^{REF}, respectively, the leakage rate will be given by:

$$\text{Leakage Rate (\%)} = 100*\frac{\left(E_{NP}^{FRX} - E_{NP}^{REF}\right)}{\left(E_{P}^{REF} - E_{P}^{FRX}\right)}$$

It should be noted that a sufficiently long time horizon has to be considered if we aim at properly accounting for variations in carbon emissions due to LUCs10. Therefore, and in order to capture a meaningful measure of TCL, the results for carbon leakage are presented in cumulative terms from 2020 (when the international climate regime enters into force) up to 2050 and to 2100.

Figure 2 shows the cumulative carbon leakage rate for the different fragmentation scenarios from 2020 to 2050 (left) and from 2020 to 2100 (right), distinguishing ICL and TCL. First, this cumulative leakage rates are consistent with those in the literature (see Böhringer et al. 2012). Second, we see that in both time periods the total carbon leakage rate decreases with the size of the coalition implementing the international climate regime. In fact, the highest total leakage rate in the period 2020-2050 is in the FR1 scenario (28%) and the lowest in the FR6 scenario (6%). Third, we see that the ICL rate is much lower than the TCL rate. In the period 2020-2050 the ICL rate ranges from 3% to 14% and the TCL rate ranges from 21% to 93%. Four, we can observe that the ICL rate dominates over the long run, where the rates for total leakage and ICL almost coincide.

Figure 2. Global carbon leakage rate for 2020-2050 (left) and 2020-2100 (right)



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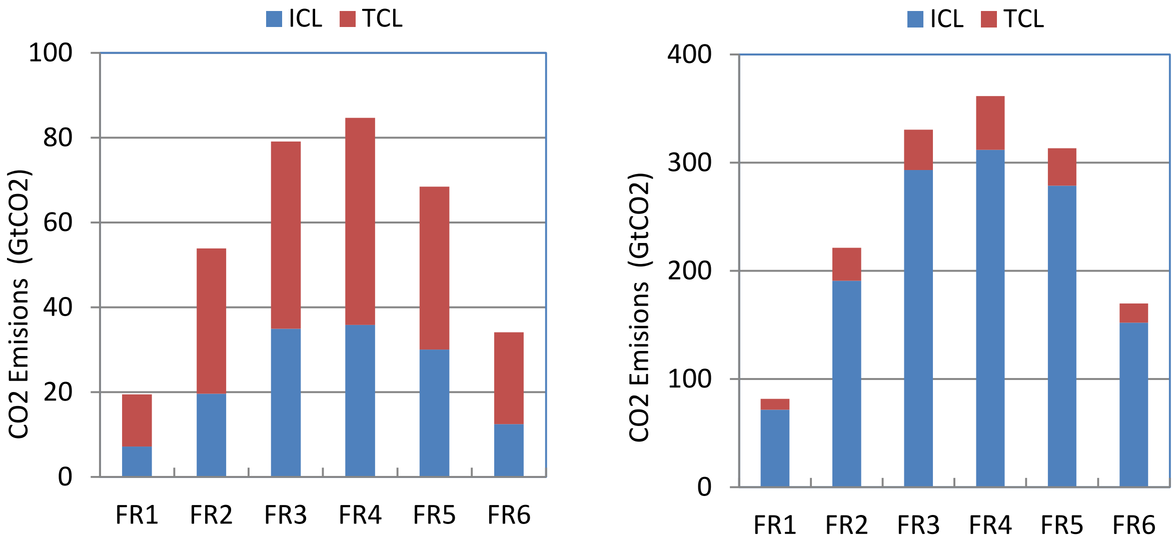
[10] Even though all the carbon that is stored in a forest converted to a cropland is released immediately, it takes time for afforestation to build up all the carbon storage potential in the new forests.

Figure 3 shows the cumulative carbon leakage in absolute terms associated to the different fragmentation scenarios from 2020 to 2050 (left) and from 2020 to 2100 (right). In the period 2020-2050 we find that cumulative carbon leakage is in the range from 22 GtCO2 to 98 GtCO2 and that the highest values occurs in scenarios FR3, FR4 and FR5. The relation between leakage (in absolute terms) and the size of the coalition implementing the climate regime shows an inverted-U shape: it takes lower values when the size is small (FR1), it takes higher values as the size grows (FR2-FR3), but once the coalition reaches certain critical level (close to that for FR4) increases in the size of the coalition (FR5-FR6) reduce the value of carbon leakage. This inverted-U shape can also be observed in the period 2020-2100, with the only difference that the amount of leakage is much higher in this case for every scenario. Note also that when a new region joins the climate coalition it starts reducing its emissions according to its reduction target, but on the contrary all the regions outside the coalition increase their emissions. This effect can be observed in Figure A4 (see the Appendix) where regional disaggregation of carbon leakage is presented for each of the scenarios.

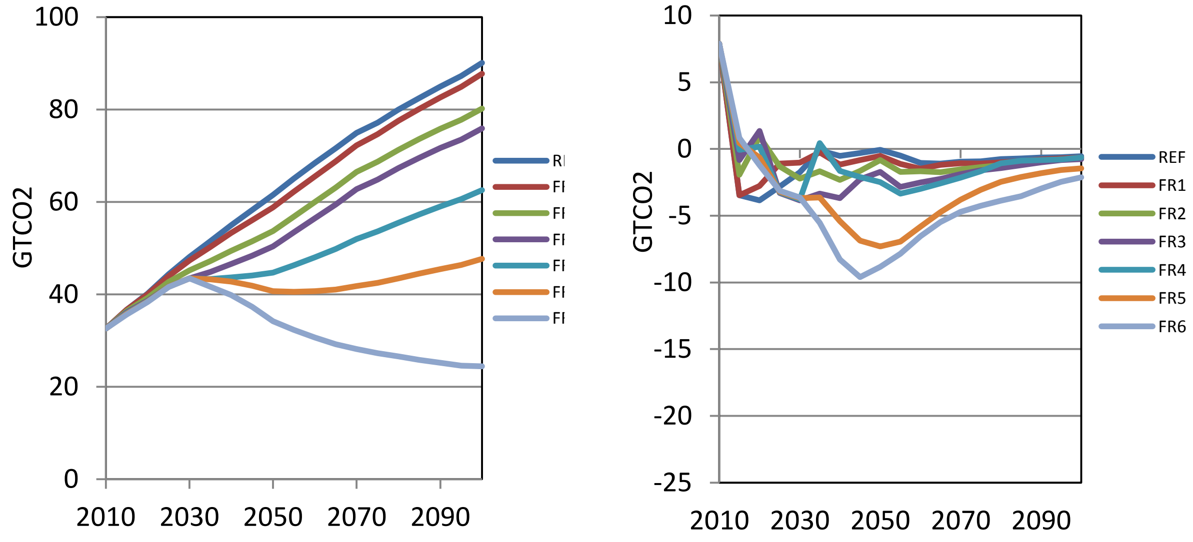
One interesting result can be found in the comparison between the TCL and the ICL effects. We can see that, in absolute terms, TCL is very relevant for the period 2020-2050. However, if the longer period 2020-2100 is considered, the ICL effect dominates. In order to explain this, let us remember that emissions related to LUCs take place mainly between 2020 and 2030 (when mitigation policies start in the developed and developing regions, respectively), but then emissions related to LUCs start to decline.

Figure 3. Global carbon leakage (GtCO2) for 2020-2050 (left) and 2020-2100 (right)



With regard to emissions, Figure 4 presents the evolution over time of emissions associated to the energy system and LUCs. In the left hand side of Figure 5 we can see that emissions associated to the energy system increase monotonically over time not only for the REF scenario but also for scenarios FR1, FR2 and FR3, where only developed countries take part in the international climate regime. For emissions associated to the energy system to curb down it is necessary that developing regions join the coalition (scenarios FR4, FR5 and FR6). However, emissions associated to the energy system will rise up again around 2050 if the only developing regions joining the international climate regime are the so-called BASIC countries (scenarios FR4 and FR5). In the right hand side of Figure 5 we show that in the REF scenario emissions associated to LUCs decrease from +8 GtCO2 in 2010 to -0.5 GtCO2 in 2100, whereas in the rest of the scenarios afforestation drive emissions associated to LUCs to negative values (from -0.5 GtCO2 in FR1 to -9.6 GtCO2 in FR6) before 2050 and monotonically converge to values closer to those of the REF scenario by the end of the century.

Figure 4. Global emissions (GtCO2): energy system (left) and land-use changes (right)



Finally, in Table 2 we show the mitigation rates in 2050 by scenario and regions. The shaded area represents those regions that are in the climate coalition in each of the fragmented scenarios. We can see, for example, comparing scenarios FR1 and FR2 that although the EU has to meet its objective of a 80% reduction of total CO2 emission by 2050, this commitment can be relaxed slightly when the US enters into the coalition since its marginal abatement costs are lower. Also, we can see that in those regions outside the grey area, (non-participant regions) emissions are always higher in any of the fragmented scenarios that in the REF scenario, due to the presence of carbon leakage.

Table 2. Mitigation rates (%) by 2050 (compared to 1990)

	REF	FR1	FR2	FR3	FR4	FR5	FR6
EU27	1%	-80%	-78%	-79%	-79%	-78%	-78%
USA	49%	51%	-88%	-90%	-91%	-92%	-92%
Other Developed	70%	75%	82%	-75%	-76%	-77%	-78%
China	288%	292%	298%	307%	140%	138%	103%
Brazil+ India+ S Africa	365%	369%	383%	398%	407%	117%	101%
ROW	189%	192%	202%	214%	221%	226%	85%
Russia, ME and Africa	84%	87%	93%	100%	104%	103%	102%
Global	**131%**	**121%**	**100%**	**86%**	**63%**	**38%**	**12%**

Figure 4 and Table 2 suggest that there are important differences between scenarios in emission reduction effort. Therefore we should be cautious when comparing the effect of these scenarios in terms of mitigation cost or climate change control achievement as we will see in the following sub-sections.

5.2 Effects in the global energy system

An analysis of the changes in the global energy system in response to a fragmented climate regime will help understanding of the driving forces behind ICL. As it was mentioned previously, the channel through which ICL takes place in our model is the fossil fuel price channel.

Figure 5. Global primary energy mix in consumption in 2050 (EJ/year)

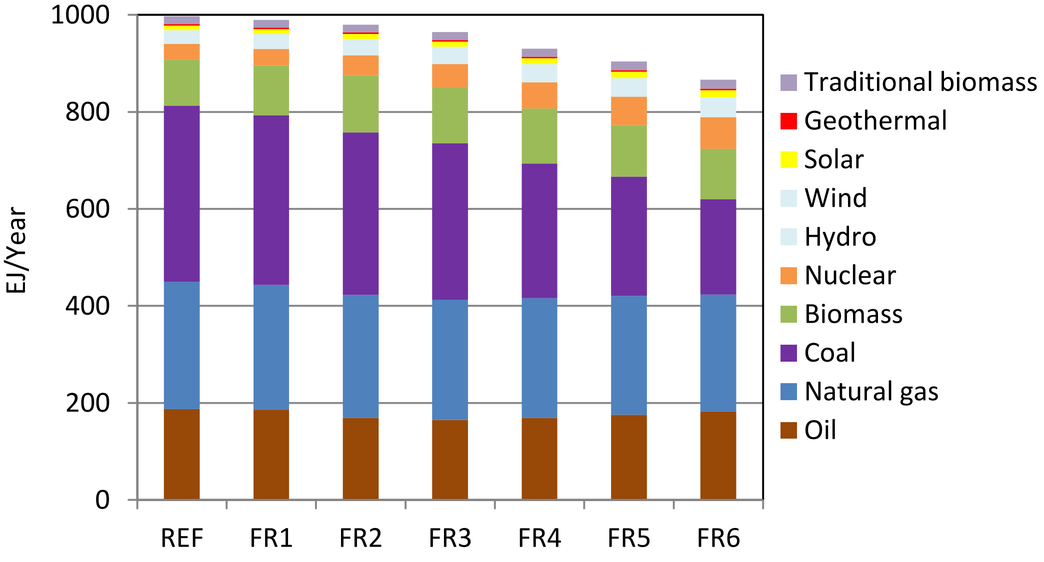
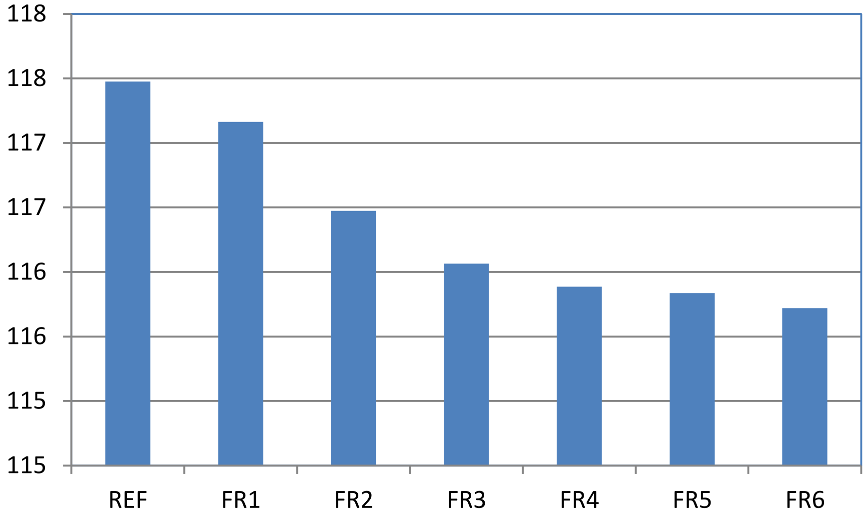


Figure 6 shows the global primary energy mix in 2050. As the size of the climate coalition increases the share of fossil fuel in total primary energy demand decreases from 82% in the REF scenario to 76% in the FR3 scenario. This reduction in demand for fossil fuels causes a drop in the price of fossil fuels. In Figure 7 we show the change in the fossil fuel price index[11] in 2050. Even though the change in the fossil fuel price index is limited for every scenario ranging from 17.5% in REF to 15.5% in FR6, we find that the bigger the size of the coalition the lower the increase in the fossil fuel price index.

Figure 6. Global Fossil Fuel Price Index in 2050 (2010=100)



According to the results reported in Figures 5 and 6 it may seem that fragmentation of the international climate regime does not have a substantial impact on the demand (and therefore price) of fossil fuels. However, we should also consider other effects in the energy system that would simultaneously take place. First, it should be noted that climate policies will induce improvements in energy efficiency that will be translated into reduction in global energy consumption. Thus, Figure 6 shows the decreasing amount of energy consumption in primary terms in 2050 from 997 EJ (REF scenario) to 866 EJ (FR6 scenario). Second, the consideration in this model of CCS technologies allows for some amount of fossil fuels to be used also in the participating regions. Figure 7 shows that a relevant part of the global electricity mix in 2050 is still covered by fossil fuel with CCS technology (dashed bars). The greater expansion due to mitigation policies is coming from nuclear. We also see in Figures 7 and 8 that biomass does not have a prominent role in the energy system and the use biomass with CCS is marginal in all the scenarios in 2050[12]. This expansion of biomass will be explored further in the next sub-section.

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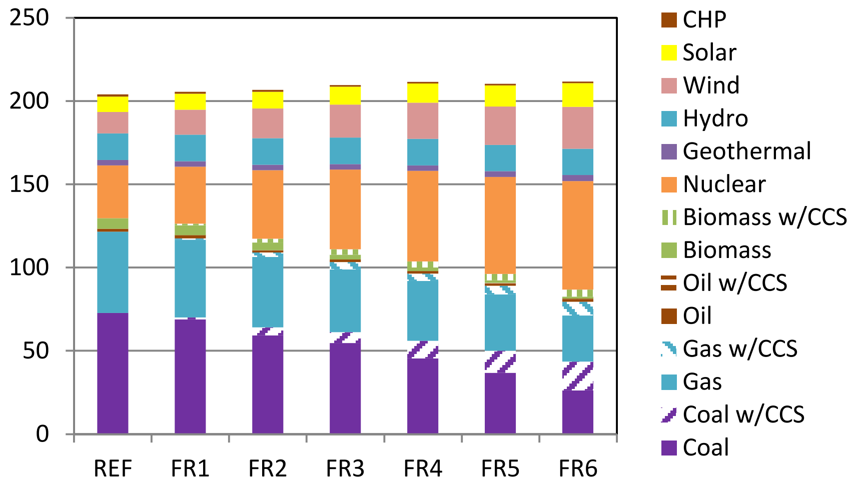
[11] The Index of Fossil Fuel includes the global price variation of crude oil, natural gas and coal. Each element is weight according to the proportion of energy (EJ) in the mix.

[12] This is also true for all the scenarios in 2100.

Figure 7. Global electricity consumption in 2050 by technologies (EJ/yr)

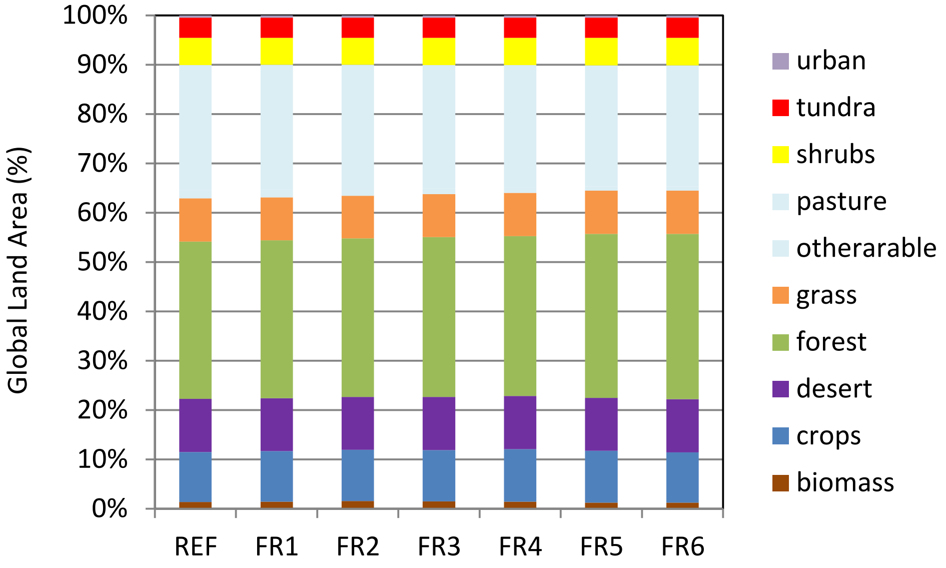


5.3 Effects in the global land-use system

The main channels for TCL are the deforestation and/or afforestation that takes place in response to fragmentation of the climate regime. As it was stated in the introductory section, all the scenarios used in this report are implemented following a UCT approach. When participating countries put an explicit value on terrestrial carbon emissions, those regions have an incentive to trade land with low carbon density (eg. crop land) for land with high carbon density (eg. forest). This will trigger afforestation in participating countries and deforestation in non-participating countries. Clearing mature forests immediately releases many years of accumulated carbon and it will take time for the afforested area to store that amount of carbon. This means that there may be temporarily an increase in LUC related emissions even if the forest area remains globally stable.

Figure 8 shows the global land allocation under different scenarios by 2050. The figure shows that the share of some land uses remains nearly constant. This is the case of urban land use (0.4 Mkm2), desert area (10.7 Mkm2) or tundra area (4 Mkm2). Others change very little. This is the case of grassland (between 8.7 and 9.2 Mkm2), pastureland (between 24.8 and 25.3 MKm2) or shrub land (between 5.5 and 5.6 Mkm2). In absolute terms the most relevant variation takes place within the land devoted to forests (between 31 and 34 Mkm2) and also, but in relative terms, in the land devoted to produce biomass (between 0.6 and 1.3 Mkm2) as well as in the crop land (between 8.7 and 9.2 Mkm2) and other arable land (0.9 and 1.6 Mkm2).

Figure 8. Global land use area in 2050 (%)



Given the importance of afforestation and deforestation in understanding TCL, we show in Figure 9 the evolution of the global area dedicated to (managed and unmanaged) forest land. In the REF scenario there is a decrease in the area dedicated to forest. However, the introduction of (fragmented) climate policy leads to an increase in the global forest area. We can even see the "jumps" in afforestation in the year in which regions start the mitigation efforts (2020 for developed countries and 2030 for developing countries).

Figure 9. Evolution of global forest area (Mkm^2)

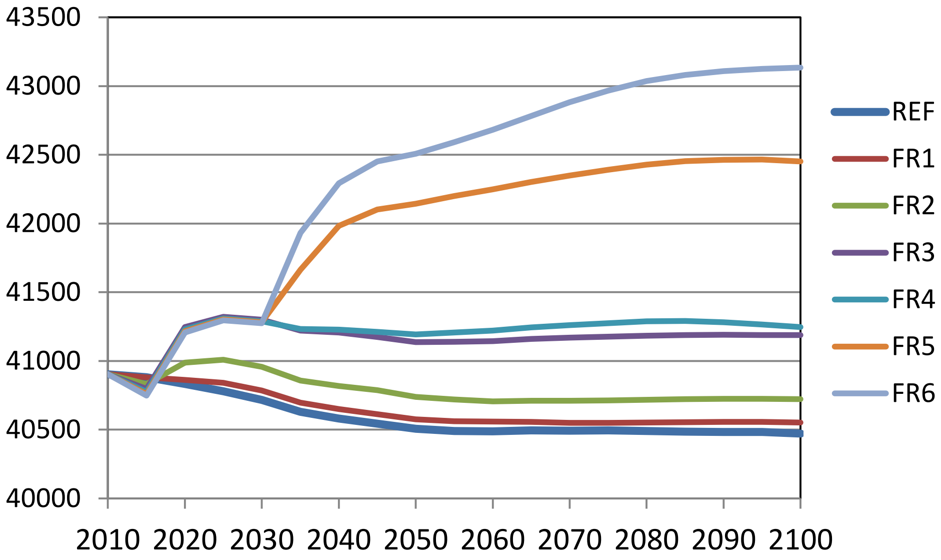


Figure 10 shows the regional pattern of afforestation and deforestation by regions in 2050. When a country enters into the climate coalition it starts increasing the forest area and exactly the opposite happens for those countries outside the climate coalition. It is very significant the amount of reforestation in Brazil when the country joins in the climate coalition. It is also very significant the amount of deforestation that takes place in every scenario in non-participating countries (Africa and Russia).

Figure 10. Change in forest area by regions in 2050 (compared to REF)

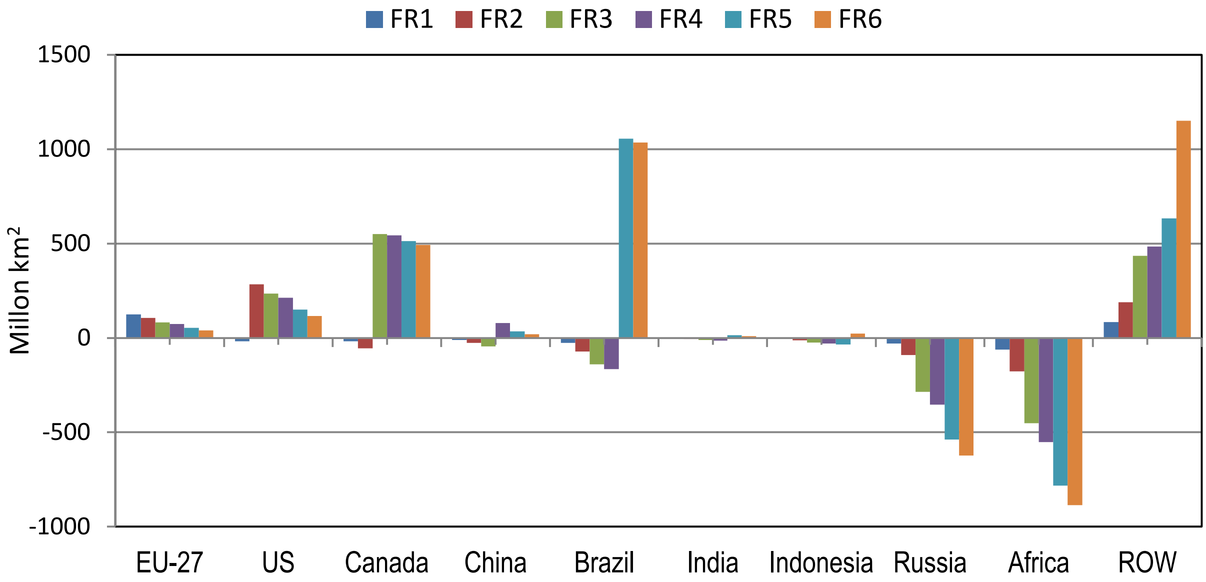
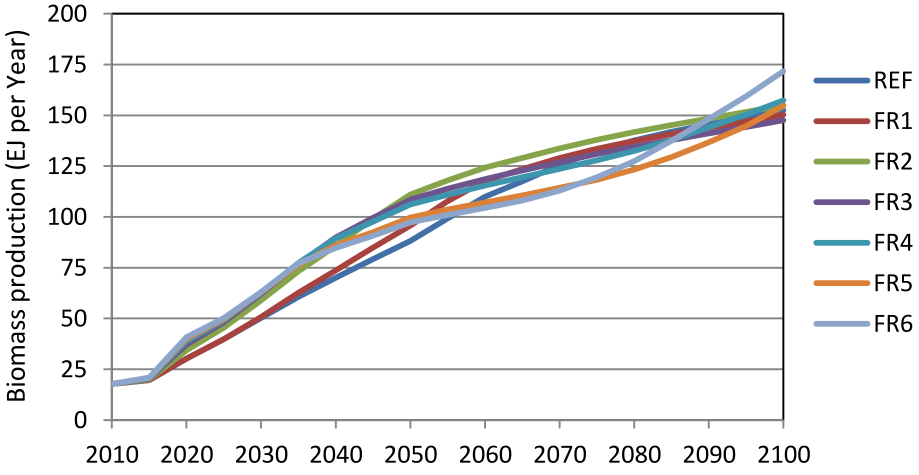


Figure 11. Global biomass production (EJ/year)



As it is shown in Calvin et al 2014 the more relevant trade-off from a UCT framework is the huge increase in the price of food because of the price on terrestrial CO2. Climate policy fragmentation does not affect much to the global biomass production, as it showed in

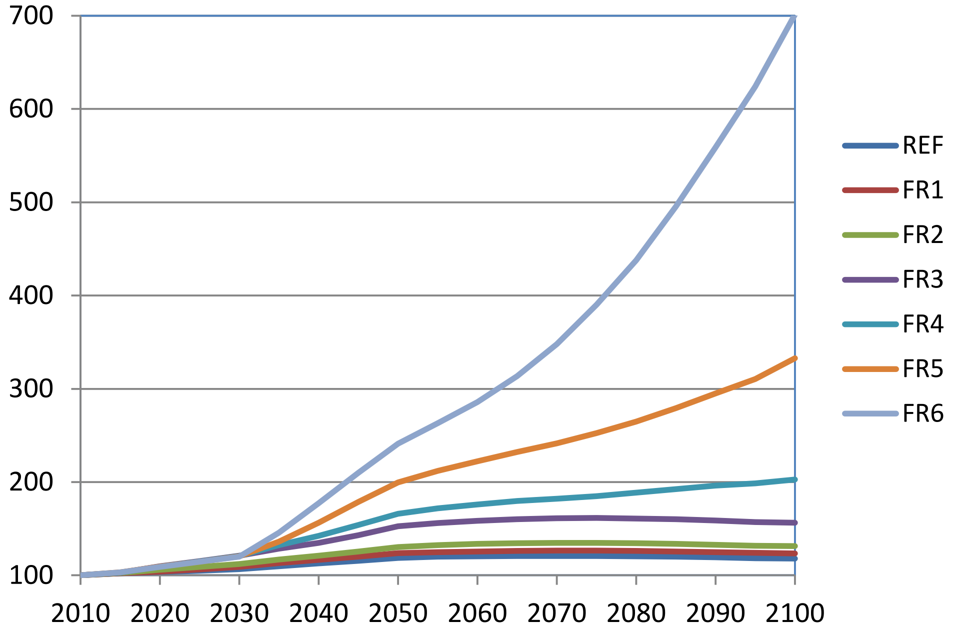
Figure 11. Similarly, fragmentation does not affect much to the global crop area as Table 4 shows. However, in both cases fragmentation forces a shift of production of biomass/food to those regions that are outside the climate coalition. That implies that production is not undertaken in those places where the productivity is higher. Thus, fragmentation will intensify this increase in the price of food.

Table 3. Change in the land area dedicated to crops in 2100 (compared to REF)

	FR1	FR2	FR3	FR4	FR5	FR6
Participating	-35.9%	-34.5%	-37.8%	-30.4%	-23.4%	-15.0%
Non-participating	4.0%	9.4%	18.4%	25.9%	38.2%	39.6%
Global	1.4%	2.3%	2.6%	4.9%	3.5%	1.3%

The impact on the global food price index[13] is shown in Figure 12. The higher the mitigation target (and the level of afforestation) the higher the increase in the price of food. In 2050 the price of food could increase by a factor of 2 and 2.5 in FR 5 and FR6, respectively. In 2100 the prices increase by a factor of 3 and 7 in FR 5 and FR6, respectively. The highest increases in prices are in the price of animal products such as beef and poultry. However, food demand in GCAM has no or very low price elasticity, so there is no relevant changes in diet patterns (see Figure A5 and A6 in the Appendixes)

Figure 12. Global Food Price index (Base 2010=100)



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[13] The Food Price Index includes the global price variation of the ten crops and six animal categories include in the GCAM model. Each element is weighted according to the proportion of calories that it provides in the global diet (see Figure A5), which don´t change much in

However, any comparison between scenarios should be made carefully as the climate stabilization achievement is quite different as it will be shown in the next section.

5.4 Effect on the climate system and mitigation costs

Figure 13 shows the temperature change for each of the scenarios considered in this report. Consistently with emission reduction targets (see Figure 5 and Table 3) increases in average temperature in 2100 are very different. In the REF scenario temperature increase in 2100 is 3.8°C above preindustrial level, whereas in the FR1, FR2 and FR3 scenarios, due to the fact that developing regions do not take part in the international climate regime, is only slightly below such level (3.7, 3.5 and 3.4°C, respectively). Even in the FR6 scenario, where only Russia, Middle East and Africa are outside the international climate regime, the increase in the mean global temperature (2.4°C) exceeds the critical threshold established by the UNFCCC to prevent "dangerous anthropogenic inference with the global climate system". This due to two factors: (1) the increasing emissions in non –participatory regions due to the carbon leakage effect and (2) the timing of mitigation that in the fragmented climate policy scenarios is delayed to 2030 for developing regions.

Figure 13. Global temperature change, 2010-2100 (°C)

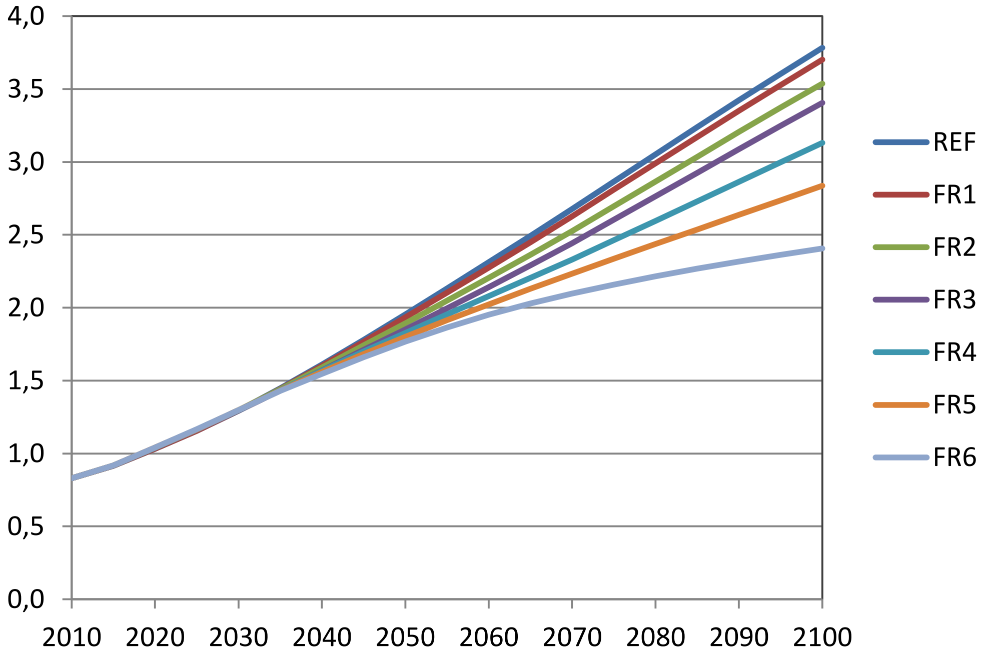
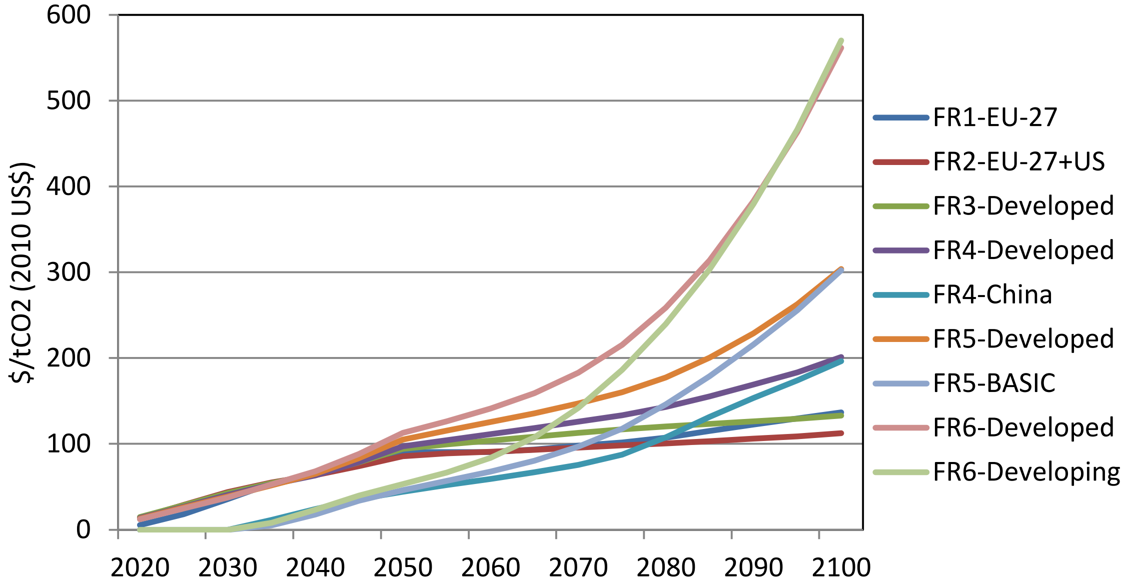


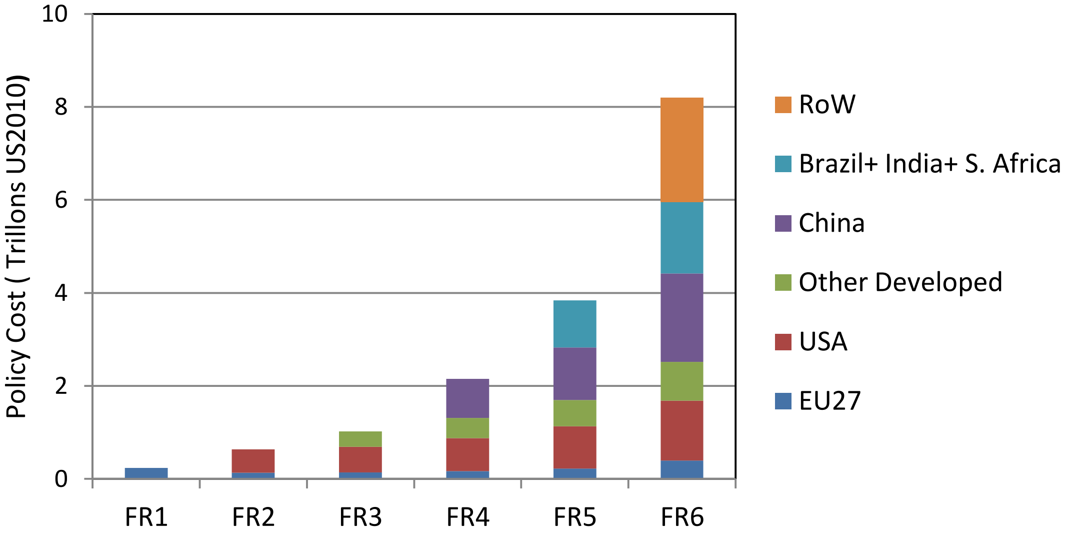
Figure 14 shows the different price of CO2 associated to each of the scenarios. Note that in scenarios FR4, FR5 and FR6 there will be two "bubbles", one for developing countries and the other for developed countries, and therefore there will be two different prices.

Figure 14. CO2 prices by regions ($/tCO2 US$2010)



Another measure of the cost of mitigation is the area under the marginal abatement cost curve, a measure of the deadweight loss of the policy. The cumulative discounted cost of mitigation (2020-2100) in Figure 15 exhibits a similar pattern to that of carbon prices; a higher price of CO2 means a higher cost of mitigation. The cumulative discounted cost of mitigation is the highest in the FR6 scenario (8.2 trillion US2010) followed by the FR5 (3.8 trillion US2010). However, the regional distribution of those mitigation cost is different among regions depending on whether they are participating or non-participating regions in the international climate regime.

Figure 15. Policy cost for the different scenario n 2100 (Trillion 2010$)



The regional cost of mitigation can also be observed in Table 5 where the policy cost by 2100 is measured in terms of GDP. These results are consistent with those contained in Table 3. The regions outside the climate coalition have no mitigation target and therefore the policy cost in terms of GDP is 0%. However, regions that are in the climate coalition in each of the fragmented scenarios have a policy cost. The total policy cost increases from 0.13% of global GDP in FR1 to 0.44% in FR3 and to 2.49% in FR6. For some regions the participations of new regions in the coalition reduces their mitigation cost. This is the case of UE-27 if US joins the coalition. In other situations, such as the case of China when other BASIC countries enter join the coalition, mitigation costs increase. This effect depends on how the mitigation options with lowest costs are distributed among the regions, since the market will allocate more mitigation effort to these regions.

Table 4. Policy cost by regions in 2100 (% of GDP)

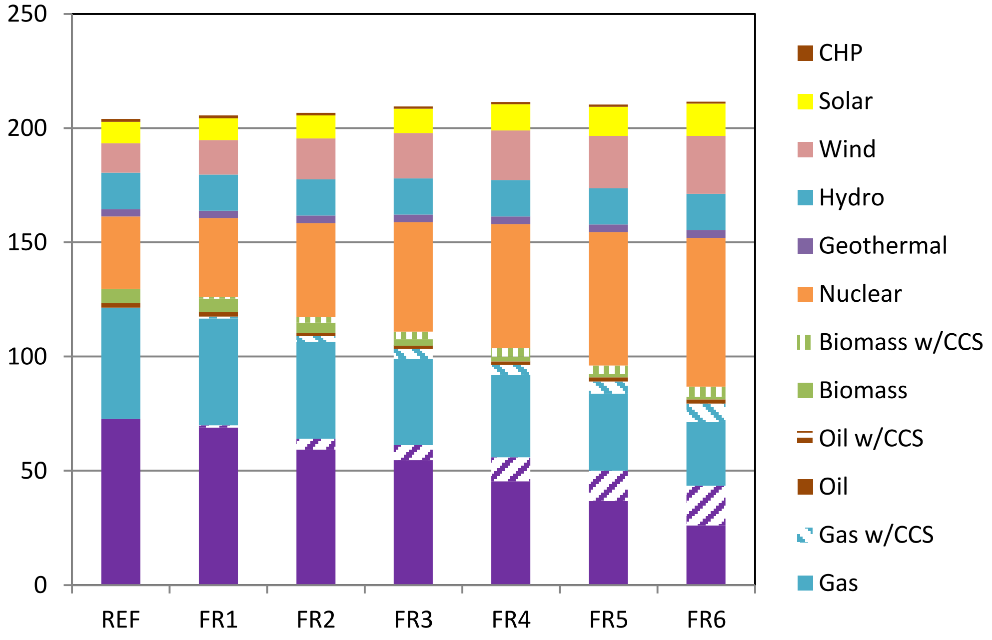
	FR1	FR2	FR3	FR4	FR5	FR6
EU27	0.90%	0.50%	0.50%	0.55%	0.70%	1.17%
USA	0.00%	1.01%	1.02%	1.21%	1.41%	1.82%
Other Developed	0.00%	0.00%	0.94%	1.14%	1.38%	1.90%
China	0.00%	0.00%	0.00%	1.73%	2.07%	3.08%
Brazil+ India+ S. Africa	0.00%	0.00%	0.00%	0.00%	3.29%	4.29%
RoW	0.00%	0.00%	0.00%	0.00%	0.00%	3.83%
Russia, ME and Africa	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total	0.13%	0.30%	0.44%	0.82%	1.31%	2.49%

6 Implications for the European Union

In this section we will proceed in two steps. First, we will comment on the global effects of EU climate policy. Second we will zoom in on the effect of climate fragmentation for the EU-27, focusing on the changes in the energy system, the land-use system and the costs of climate policy under different fragmentation scenarios.

If we are to discuss the global effects of EU climate policy, the first scenario we should look at is the FR1 scenario, where the EU takes on the unilateral commitment of reducing emissions by 80% by 2050 (and by 88% in 2100, following a “convergence hypothesis”) and no other region makes any mitigation effort beyond “business as usual” behavior. We know from Figure 13 that the impact of this policy towards the achievement of the climate stabilization target will be very small: the global mean temperature increase will be reduced just by 0.1°C at the end of the century compared to the reference scenario. Two factors explain this result. The first one is the small share of the EU-27 in global GHG emissions, which is expected to account for roughly 7% of total global CO2 emissions in 2050. The second is the carbon leakage effect arising from the fragmented climate regime, which would imply an accumulated increase of 5 GTC in emissions between 2020-2050 in the rest of the world (leakage rate of 28%) as it has been shown in Figures 3 and 4. In fact, this is the highest leakage rate in all the possible fragmentation scenarios considered in this report. If other countries such as the US and China join the coalition (scenario FR4), the global mean temperature increase would be lower in 2100 than what it would be in scenario FR1 but still above 3 °C.

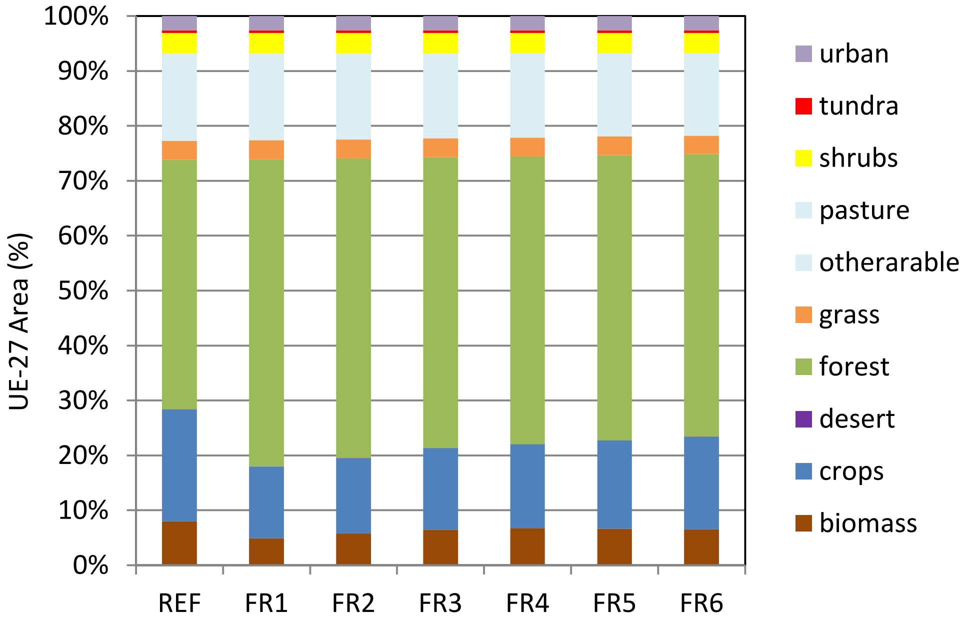
Figure 16. EU-27 primary energy consumption in 2050 (EJ/yr)



The very limited impact of unilateral mitigation efforts of the EU (and even of all the developed countries) on the climate system should not come to a surprise and has been already reported in other studies. However, this report shows that there are also other effects both inside and outside the EU that have not been thoroughly studied.

Figure 16 shows how the composition of primary energy consumption responds to fragmented climate regimes. The most important effect can be found in coal with a reduction from 21.6 EJ/year in REF to 7.6 EJ in FR1 and 4.6 EJ in FR6, whereas the remaining coal, gas and oil is used in the power sector in combination with CCS technology. Another important effect is the increased presence of biomass in the energy mix, which grows from 8.2 EJ/year in REF scenario to 18.6 EJ in FR1 and 14.4 in FR6. However, the increase in demand for biomass is not coupled with an increase of biomass production in the EU. The UCT regime gives incentives to store carbon in EU's land through afforestation and to reduce the land devoted to crop and biomass production. Figure 17 shows the distribution of land uses with forest area increasing from 1,829 Mkm2 in REF to 2,249 Mkm2 in FR1 and 2,068 Mkm2 in FR6. Table 6 shows that the area devoted to crop[14] and biomass production decreases 36 and 38% in FR1, respectively, and 17 and 18% in FR6. Therefore, EU climate policies will not only affect energy and industrial systems, but also could have an impact on the agro-food systems.

Figure 17. EU-27 land use area in 2050 (%)



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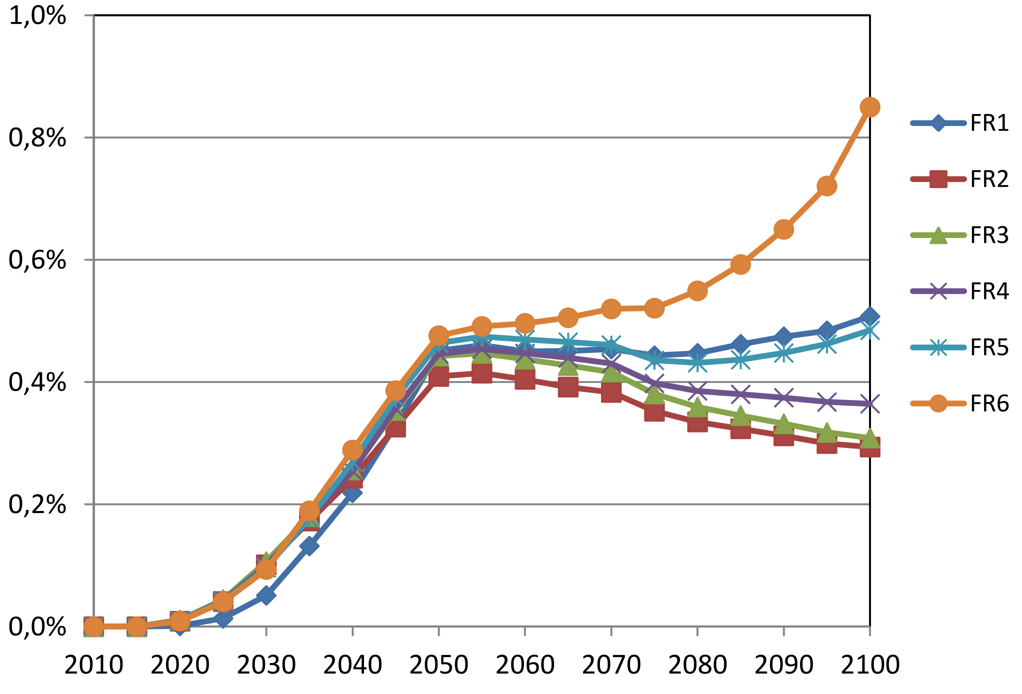
[14] The 36% decrease in area for Crops in scenario FR1 (17% decrease in scenario FR6) with respect to the area devoted in the REF scenario may also be considered a serious concern in terms of food security.

Table 5. Area for food and biomass in the EU-27 in 2050

	Area for Crops		Area for Biomass	
	Area (thousand km2)	% REF	Area (thousand km2)	% REF
REF	820		320	
FR1	526	-36%	197	-38%
FR2	551	-33%	232	-27%
FR3	597	-27%	232	-27%
FR4	614	-25%	272	-15%
FR5	647	-21%	266	-17%
FR6	677	-17%	263	-18%

Finally, climate policy costs for the EU-27 under different fragmented scenarios are presented in Figure 18. It is relevant to notice that increasing the size of the climate coalition can reduce, in some cases, the cost of mitigation for the EU-27. For example, in 2050 the cost for the EU-27 in FR1 is 0.45% of GDP, the same that in the FR4 scenario. In 2100 the cost for the EU-27 in FR1 is 0.51 % of GDP below the FR6 scenario but still above FR2 and FR3. The cost of mitigation for the EU will be influenced by final mitigation effort and by the possibility exploiting cheaper mitigation options outside the EU.

Figure 18. Policy cost for the UE-27 (% of GDP)



7 Conclusion

The UNFCCC process has experienced a shift from a top-down legally binding policy architecture towards a bottom-up a approach in which countries decide individually on voluntary pledges. Therefore, it is expected that climate action will remain fragmented for a long time. One of the main concerns about fragmented climate regimes is carbon leakage, both the carbon leakage associated to FFI (ICL) and the carbon leakage associated to LUCs (TCL). In this report we have considered the implementation of a fragmented climate policy under a UCT framework with the objective of analyzing the effects such a policy on both types of carbon leakage as well as emissions, energy systems, land uses, climate conditions and mitigation costs both in the EU and the rest of the world.

One of the findings in this report is that unilateral mitigation effort by the EU along the lines of the Roadmap for moving to a competitive low carbon economy in 2050 (COM, 2011) if other major emitters (mainly those in developing regions) do not follow will have a very modest impact on temperature changes at the end of the century and substantial carbon leakage (both ICL and TCL) will take place.

With regard to carbon leakage, we can expect TCL to be the dominant type of leakage up to 2050, and ICL to take over during the second half of the century, once the carbon storage potential of afforestation is fully exploited.

In line with other studies in the literature (see Calvin et al. 2009), we find that the implementation of international climate policy under a UCT framework (the same tax for industrial and terrestrial carbon emissions) will increase forest land at a global scale. However, our analysis of fragmented climate regimes allows us also to show that different fragmentation scenarios will lead to different patterns of deforestation and afforestation across regions. The implications of this land use changes in terms of provision of ecosystem services and food security for affected regions should be taken into account.

We should keep in mind some caveats, however. First, this report has examined an idealized UCT international policy architecture leaving aside the difficulties associated to the implementation of a policy that taxes terrestrial emissions. Second, part of our results relies on the assumption that CCS technology will be commercially available by 2020, which according to recent studies such as UKRC (2014) is a very optimistic assumption. Third, our results on land use are very dependent on assumed exogenous crop productivity improvements (see Wise et al. 2009 and Kyle et al. 2014). The change in productivity until 2050 is based on FAO estimates (Bruinsma 2003), but then ad hoc assumptions are made with regard to the reduction of the productivity gap between regions. Fourth, the effect of climate on yields is not included and, although this issue is beyond the scope of this report, is one of the improvements in the modelling approach currently being discussed by the IAM and GCAM community.

With regard to future research directions, one possibility would be to extend the analysis to consider the introduction *biodiversity*-sensitive forest preservation incentives in the *international* climate regime, having seen that one important implications of a UCT-type of instrument in a fragmented climate regime is that leads to deforestation in non-participatory countries.

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9 Appendix

Table A1. Regional disaggregation of GCAM 4.0 and classifications

Developed Countries	Developing Countries	Non-Participants
Argentina	Brazil	Africa_Eastern
Australia_NZ	Central America and Caribbean	Africa_Northern
Canada	Central Asia	Africa_Southern
EU-12	China	Africa_Western
EU-15	Colombia	Middle East
Europe_Non_EU	Europe_Eastern	Russia
European Free Trade Association	India	
Japan	Indonesia	
Mexico	Pakistan	
South Korea	South Africa	
Taiwan	South America_Northern	
USA	South America_Southern	
	South Asia	
	Southeast Asia	

Figure A1. Population Projections, 2010-2100

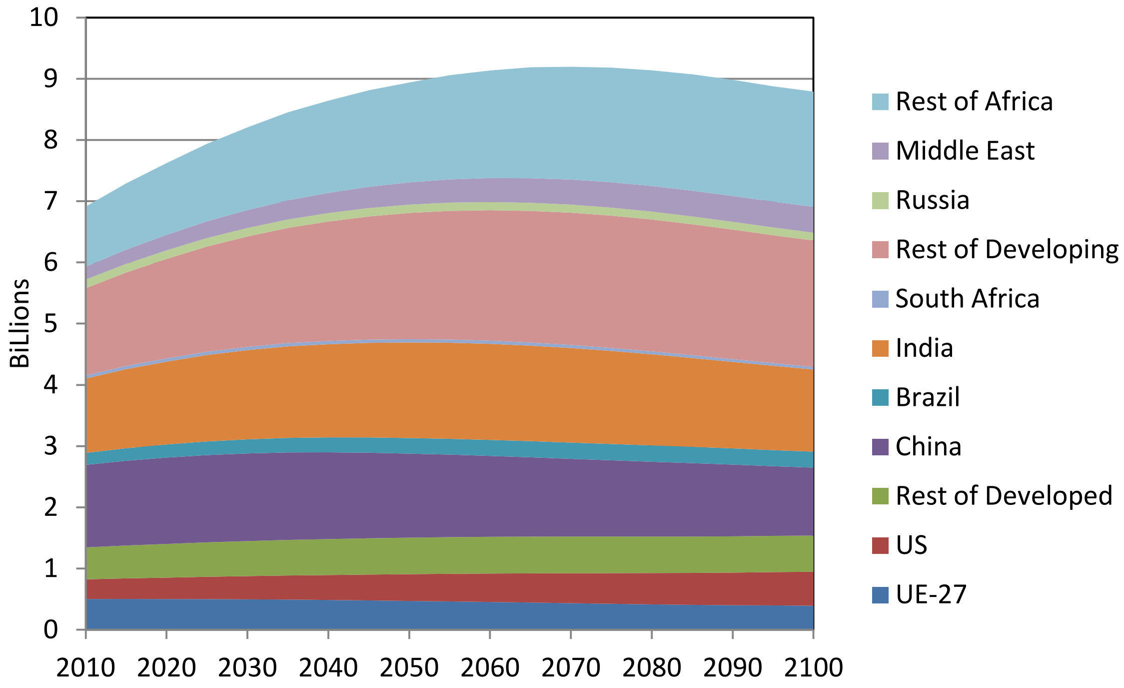

Figure A2. GDP Projections (MER), 2010-2100

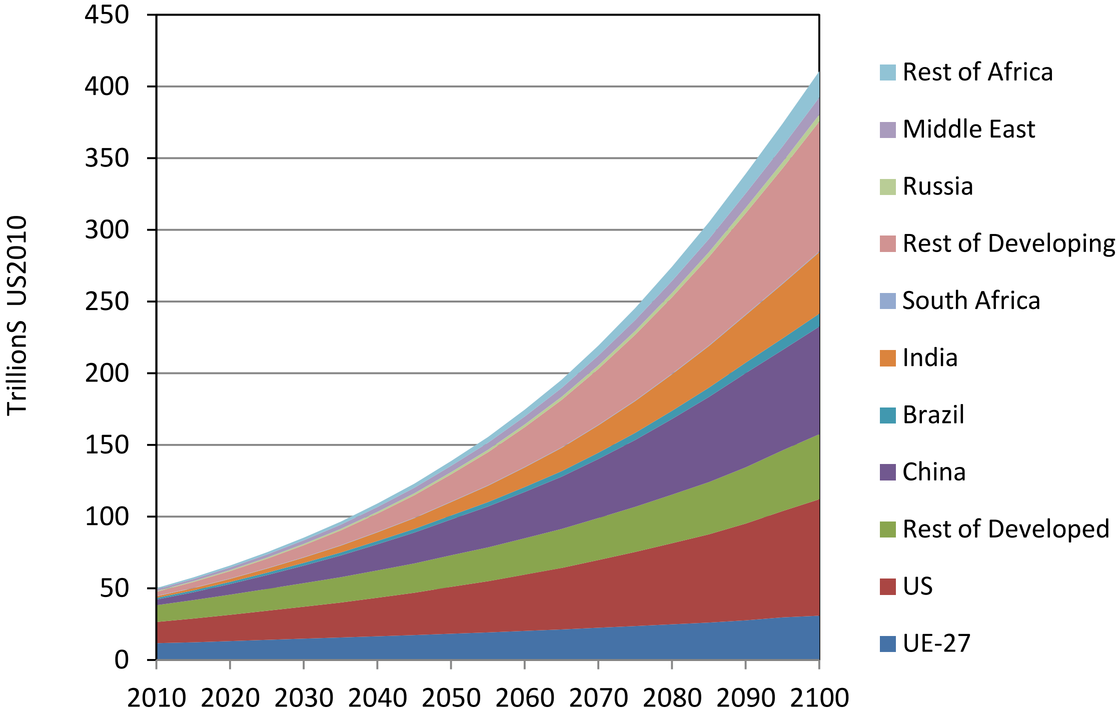

Figure A3. Emissions per capita by regions and scenarios, 2010-2100 (tCO2)

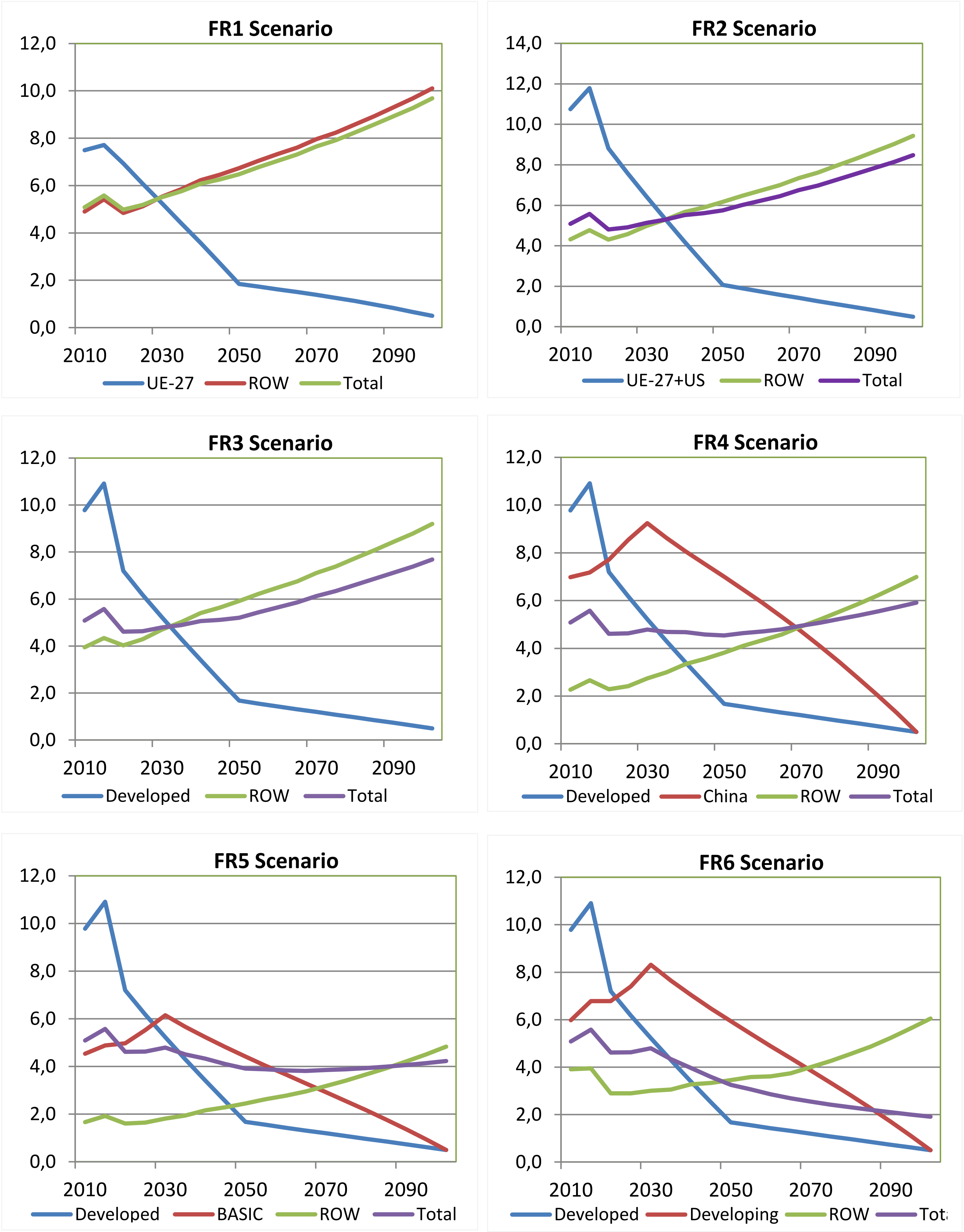

Figure A4. Carbon leakage by regions and scenarios, 2010-2050 (GtCO2)

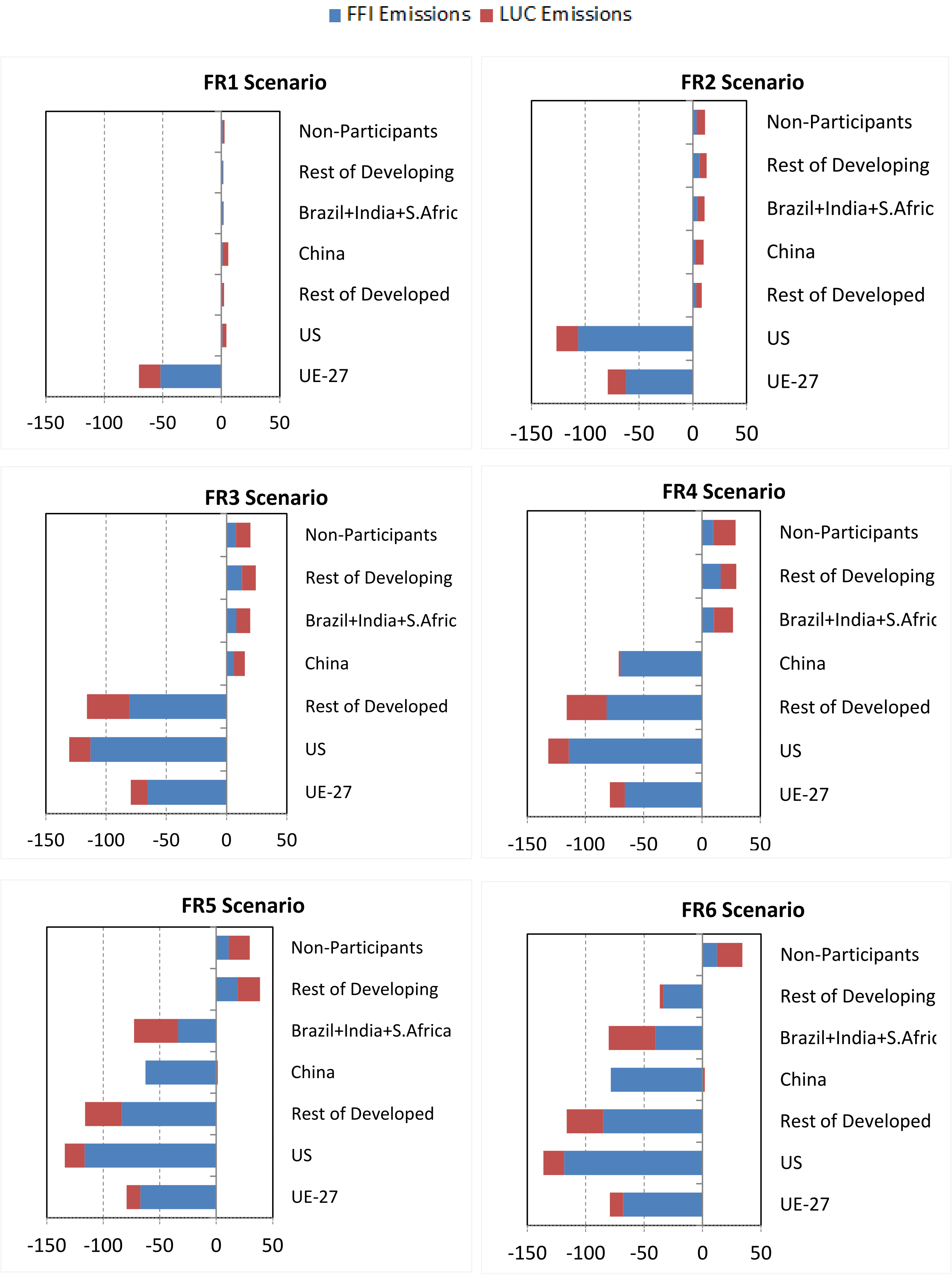

Table A2 Yields and cost for relevant dedicated bioenergy crops

	Region	Average Crop Yield (kg/m2/yr)	Energy Content (MJ/kg)	Energy Yield (MJ/m2)	Cost ($2008/GJ)
Miscanthus	Western Europe	1	16	16	3.5
Willow					
	Eastern Europe	1	19	19	2.3
	Western Europe	1	19	19	2.3
	China	1	19	19	2.3
	US	1	19	19	2.3
Eucalyptus					
	Africa	1.2	19.4	23	2.4
	Latin America	1.2	19.4	23	2.4
Jatropha (oil)					
	Africa	0.14	40	5.6	4.2
	Latin America	0.14	40	5.6	4.2

Source: (Kyle 2011)

Figure A5. Global diet from different categories in the Reference Scenario

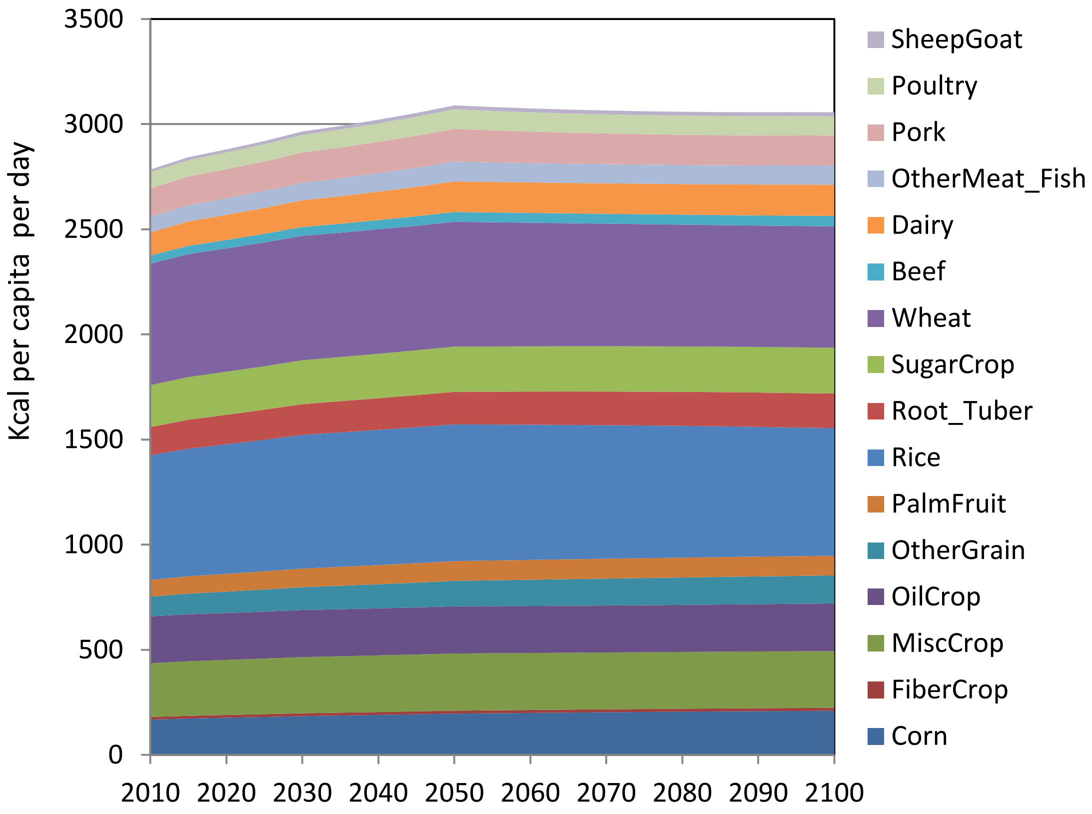

Figure A6. Global diet from different categories in the FR6 Scenario