PBL Netherlands Environmental Assessment Agency

GREENHOUSE GAS EMISSION REDUCTION TARGETS FOR 2030 CONDITIONS FOR AN EU TARGET OF 40%

POLICY STUDIES

Greenhouse gas emission reduction targets for 2030

Conditions for an EU target of 40%

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Main findings

The Dutch Government calls for a conditional, European greenhouse gas (GHG) emission reduction target of 40% below 1990 levels by 2030, to be achieved within Europe, dependent on adequate global action and the adequate safeguarding of the competitiveness of EU industries (Dutch Government, 2011). To be able to define these conditions more concretely, PBL has been asked to evaluate two specific issues:

1. What efforts, in case of such a 40% reduction target, would be required by other countries according to different effort-sharing regimes for allocating emission allowances (taking into account differences in economic development).
2. What would be the economic impact for the EU if other EU countries take on less stringent or no climate targets.

The analyses cover the period from 2020 onwards, at emission levels based on countries' least ambitious pledged reduction targets for that year (20% below 1990 levels for the EU).

The main findings are:

- For the main developed countries, the effort-sharing regimes lead to the following ranges in reduction targets (all expressed relative to 1990 emission levels): 25% to 31% for the United States, 38% to 48% for Japan, 26% to 41% for Canada, and 14% to 27% for Russia.
- For some main developing countries, the ranges in reduction targets are (all expressed relative to baseline levels): 19% to 34% for China, 13% to 17% for India, 30% to 37% for Mexico, 32% to 49% for Brazil, and 12% to 21% for Indonesia.
- Direct mitigation costs for achieving the EU 40% target are projected to be 0.25% to 0.4% of GDP by 2030. The global average cost for staying within an emission range consistent with 2 °C is projected to be at least 0.43% of GDP, assuming that emissions are reduced wherever it is cheapest to do so.
- With equal costs as share of GDP for all countries by 2030, a 40% reduction target would result in a global emission level that is higher than the range consistent with achieving the 2 °C climate target.
- To arrive at a global emission level that is consistent with the 2 °C climate target, with equal costs as share of GDP for all countries by 2030, the EU would need to reduce emissions by 45% to 47% relative to the 1990 level.
- EU welfare losses resulting from achieving the EU 40% target are projected to be about 0.3% in the case of global action and 0.4% in the case of EU unilateral action, in which case almost one third of the reduction in the EU is projected to be offset by increased emissions in the rest of the world (carbon leakage). This is mainly due to lower energy prices caused by a decrease in EU energy demand.
- The projected reduction in air pollution resulting from the 40% reduction target will be 17% below baseline levels by 2030. This would lead to a decrease in deaths

from air pollution of about 3.5% relative to the baseline.

- The uncertainty ranges in the results may be larger than the ranges given here. More insight into the uncertainty ranges could be obtained by using different models to perform these calculations.

Summary

The long-term Dutch and European climate policy targets focus on limiting global temperature change to 2 °C above pre-industrial levels. In 2007, the EU made a unilateral commitment to reduce its greenhouse gas emissions to 20% below 1990 levels. This commitment, together with an EU renewable energy target of 20% for 2020, was translated into EU legislation through the 'climate and energy package', which was agreed by Council and Parliament at the end of 2008.

EU leaders also made a conditional commitment to scale up the EU greenhouse gas emission reduction target of 20% to 30% by 2020, on the condition that other developed countries commit to comparable emission reductions, and that more advanced developing countries would contribute to such a global effort in a manner consistent with their individual responsibilities and capabilities. These 20% unconditional and 30% conditional targets have become part of the pledges that were entered into the Cancún Agreements (UNFCCC, 2011c). For 2050, there is 'an EU objective, in the context of necessary reductions according to the IPCC by developed countries as a group, to reduce emissions by 80% to 95% by 2050 compared to 1990', as agreed in October 2009 and reaffirmed by the European Council in February 2011. The European Commission's report 'Roadmap for moving to a competitive low-carbon economy in 2050' provides cost-efficient pathways towards an overall 80% reduction in emissions within the EU by 2050, representing reductions of between 40% and 44% by 2030. However, the EU has not decided on a greenhouse gas emission reduction target for 2030, and this is still under discussion.

The Dutch Government has called for such a greenhouse gas emission reduction target by 2030. More specifically, it has proposed a conditional, European greenhouse gas emission reduction target of 40% below 1990 levels by 2030 (Dutch Government, 2011). The conditions relate to adequate global action and the adequate safeguarding of the competitiveness of European industry. To further elaborate these conditions, PBL has been asked to shed light on a number of questions, using its integrated assessment modelling framework for the analysis. These questions are dealt with one-by-one below, with a reference to the chapter in the full results in which more information can be found. The integrated modelling framework FAIR and computable general equilibrium model WorldScan were used for the analysis. These models use information on the potential and costs of reducing greenhouse gas emissions taken from the energy model TIMER, the land-use model IMAGE and the forestry model G4M. To analyse the uncertainty in results, an analysis with abatement cost curves from the POLES energy model is included.

What are the expected trends in greenhouse gas emissions without climate policy for the largest economies up to 2030? (Chapter 2)

According to the most recent PBL baseline emission projection, global emissions will reach about 62 Gt CO_2 eq by 2030 (including CO_2 emissions from land use), up from 49 Gt CO_2 eq in 2010, if countries do not implement any climate policies. About 60% of this increase will occur in China (5.5 Gt CO_2 eq) and India (2.7 Gt CO_2 eq), while emissions in most developed countries are expected to remain more or less constant between 2010 and 2030.

What global emission level is needed by 2030 to keep the 2 °C target within reach? To what extent does the emission level in 2020 influence this level? (Chapter 3)

There are multiple pathways towards achieving a 2 °C climate target, varying from early reductions in the short term to delayed action with deeper reductions in the long term. In the literature, most emission pathways towards achieving the 2 °C target have been developed from a lowest cost perspective over the century. However, the projected global emission level resulting from the greenhouse gas emission reductions pledged under the Cancún Agreements is higher than the level under the cost-optimal pathways towards achieving the 2 °C target.

The emission level in 2020 strongly influences the emission level in 2030 consistent with 2 °C pathways. In a 2 °C cost-optimal pathway (defined as the pathway with the lowest discounted costs over the century), the global emission level by 2030 is about 41 Gt CO_2 eq, which is about 4% above the 1990 level and almost 25% below the 2010 level. With early action, the 2030 emission level could be 3 Gt CO_2 eq lower. However, if the pledges for 2020 are taken into account the global emission level consistent with a 2 °C pathway would be about 4 Gt CO_2 eq higher by 2030. This implies that a delay in emission reductions can only be compensated after 2030. Higher 2020 emission levels also imply higher costs throughout the century and a higher dependence on future technological developments, compared with a scenario with lower 2020 emission levels.

Very few studies have analysed the global emission level by 2030 consistent with 2 °C pathways that take into account the pledges made for 2020. We have therefore relied on the range given in the OECD Environmental Outlook, which does include such an emission pathway and was developed using PBL's integrated assessment models. This would result in an emission range consistent with 2 °C of about 38 to 45 Gt CO_2 eq by 2030.

Table S.1
Emission reduction targets relative to PBL baseline, 2030

	Convergence in per-capita emissions (%)	Equal carbon tax (%)	Equal relative costs (%)	Equal relative costs, 2 °C (%)	Announced targets[1] (%)
Relative to 2030 baseline levels:					
EU	-35	-35	-35	-43	
USA	-35	-38	-33	-43	
Canada	-41	-31	-26	-35	
Oceania	-43	-33	-28	-34	
Japan	-48	-40	-38	-48	
Russia	-27	-22	-14	-19	
China	-34	-27	-19	-25	
India	-16	-17	-13	-19	
Indonesia	-12	-21	-12	-19	
Mexico	-37	-35	-30	-39	-38*
Brazil	-35	-49	-32	-46	
World	-29	-28	-22	-28	
Relative to 1990 levels:					
EU	-40	-40	-40	-47	-41 – -45*
USA	-27	-31	-25	-37	-33
Canada	-30	-17	-12	-22	-14 – -18
Oceania	-22	-8	-1	-10	-1*
Japan	-45	-36	-34	-45	-36 – -43
Russia	-49	-46	-41	-44	-33
China	+163	+191	+225	+200	
India	+215	+210	+223	+203	
Indonesia	+51	+35	+52	+41	
Mexico	-9	-6	+2	-10	
Brazil	-15	-34	-11	-29	
World	+13	+14	+24	+13	

Source: PBL FAIR/IMAGE/TIMER model calculations, and based on individual country assessments according to http://climateactiontracker.org/

[1] *Announced targets are either announced or adopted targets: adopted targets are denoted by a *. The United States is the only country that has announced a target for 2030. Other countries have announced long-term targets for 2050; for these countries the implied reductions for 2030 are shown here, assuming that the targets for 2050 are reached linearly between 2020 and 2050, based on UNFCCC data (submission 2010) taken from http://unfccc.int/ghg_data/ghg_data_unfccc/items/4146.php. The targets are excluding CO_2 emissions from land use. See Annex B for more detail on announced long-term targets.*

What kind of emission reduction targets would other countries need to adopt according to different effort-sharing regimes if the EU sets an internal reduction target of 40% for 2030? (Chapter 4)

To gain insight into the range of targets for other countries that would be comparable with the EU 40% reduction target we calculated emission reduction targets for other countries based on three effort-sharing approaches. These approaches are based on either i) convergence in per-capita emissions by 2055 for the least developed countries (South Asia and Southeast Asia and sub-Saharan Africa) and by 2050 for all other countries; ii) an equal carbon tax by 2030, with regional convergence between 2020 and 2030; or iii) equal relative costs (as share of GDP) by 2030, also with regional convergence

Table S.2
Projected direct mitigation costs as share of GDP, 2030

	Convergence in per-capita emissions (%)	Equal carbon tax (%)	Equal relative costs (%)	Equal relative costs, 2 °C (%)
EU	0.24	0.24	0.25	0.57
USA	0.29	0.39	0.25	0.58
Canada	1.03	0.39	0.25	0.58
Oceania	1.07	0.48	0.25	0.57
Japan	0.51	0.28	0.25	0.58
Russia	1.57	0.75	0.25	0.57
China	1.58	0.74	0.25	0.57
India	0.13	0.14	0.07	0.17
Indonesia	0.09	0.25	0.07	0.17
Mexico	0.51	0.40	0.25	0.57
Brazil	0.27	0.82	0.25	0.57
World	0.66	0.43	0.23	0.53

Source: PBL FAIR/IMAGE/TIMER model calculations. All targets are assumed to be achieved domestically.

between 2020 and 2030. For the second and third approaches, the targets for the least developed regions are based on a tax or cost level that is 30% of that of the other countries.

Table S.1 shows the range of emission reduction targets resulting from these effort-sharing principles (in which the EU has a domestic reduction target of 40%). The regime based on equal relative costs leads to a global emission level by 2030 that is 4 to 11 Gt CO_2 eq higher than the range of a 2 °C pathway. Therefore, Table S.1 also gives reduction targets resulting from an *equal relative costs* regime that limits the global emission level by 2030 to the maximum level consistent with a 2 °C pathway (called *equal relative costs*, 2 °C).

The emission reduction targets of the United States, India and Mexico are relatively independent of the choice of effort-sharing regime. For Canada, Oceania, China and Brazil, the range in reduction targets is relatively large. This is due to a much higher reduction target for Canada, Oceania and China resulting from a *convergence in per-capita emissions* regime (due to the relatively high per-capita emissions in these countries), and for Brazil under the *equal carbon tax* regime (due to the relatively high number of low-cost measures for reducing deforestation emissions).

What targets for 2030 for the EU and other countries under a regime of *equal costs as percentage of GDP* would be consistent with the 2 °C target? (Chapter 4) How robust are these results? (Chapter 6)

Table S.1 shows that for a regime of *equal relative costs* that would lead to a global emission level just within the range consistent with 2 °C (about 45 Gt CO_2 eq), the target of the EU would need to be 47% instead of 40% below 1990 levels. The reduction targets of such a regime would lie outside the range of the three default regimes for the United States and India (and just outside the range for Mexico). These targets are relatively robust for one alternative set of cost curves with corresponding baseline projection. Using data from POLES would lead to a reduction target for the EU of 45%, compared with 47% using FAIR data. Using POLES data also leads to less stringent targets for India (4% lower), Mexico (4% lower) and Japan (3% lower).

Could the range of reduction targets lead to i) higher costs for richer countries, ii) similar costs for countries with similar welfare levels, and/or iii) countries profiting from climate policy, even when the benefits of reduced climate change are not taken into account? (Chapter 5)

Table S.2 shows the projected direct mitigation costs in 2030, as a percentage of GDP, of domestically achieving the targets given in Table S.1. The projected cost of achieving the EU 40% target is about 0.25% of GDP in 2030. This rises to almost 0.6% of GDP for the *equal relative costs*, 2 °C regime, in which the EU has a reduction target of 47% below the 1990 level. This relatively large increase is due to only more expensive reduction measures being available for reductions of more than 40%. The differences in costs between regimes and countries mainly reflect the differences in the emission reduction targets.

The *convergence in per-capita emissions* regime shows the largest differences in costs between regions. For Russia and China, direct mitigation costs as share of GDP are even a factor of six to seven higher than those of the EU in this regime. This outcome is a result of a regime based on per-capita emissions not taking into account circumstances such as mitigation potential. This potential is limited for Russia due to their large overcapacity in existing coal-fired power plants, which prevents the building of new, low-carbon power plants. The potential for reducing emissions is also limited for China: China has expanded its energy sector considerably with coal power plants in the past decade, which makes replacement of or adjustments to these investments very expensive, so that it is more difficult for China to move to low-carbon technologies.

Mitigation costs for Russia, China, India, Indonesia and Brazil are relatively high under an *equal carbon tax* regime. This is mainly because these regions have relatively high emission intensities (China, India and Russia) and/or a large potential for reducing land-use emissions (Brazil, Indonesia and Russia).

The reduction targets do not lead to higher costs for richer countries, for the reasons mentioned above. The projected welfare losses, which take into account indirect costs of mitigation policies, are also not necessarily higher for richer countries for the regimes analysed. Welfare losses are relatively high for fossil fuel exporting countries such as Russia. By definition, costs between countries are similar in an *equal relative costs* regime, but for the other regimes large differences in costs were found. As we have assumed that all targets are achieved through domestic emission reduction, we do not project that countries profit from climate policy.

How robust are the results for different assumptions about baseline and cost curves? (Chapter 6)

To test the robustness of the range of reduction targets and related costs found for the various countries we calculated emission reduction targets and mitigation costs based on cost curves from a different model (the POLES energy model). For regimes based on convergence in per-capita emissions and costs, the emission reduction targets and mitigation costs seem to be relatively robust for this different set of cost curves. For the *equal carbon tax* regime, the targets and costs are not robust since the uncertainty in the carbon tax level needed to achieve the EU 40% target is substantial. Using the POLES cost curves would increase the carbon tax level to achieve the EU 40% target from USD 80/t CO_2 to USD 150/t CO_2. The carbon tax level as found by FAIR is similar to the level found in the Roadmap 2050 study (European Commission, 2011). The EU target for the *equal relative cost, 2 °C* regime is 45% below 1990 levels according to the POLES cost curves (compared with 47% using FAIR).

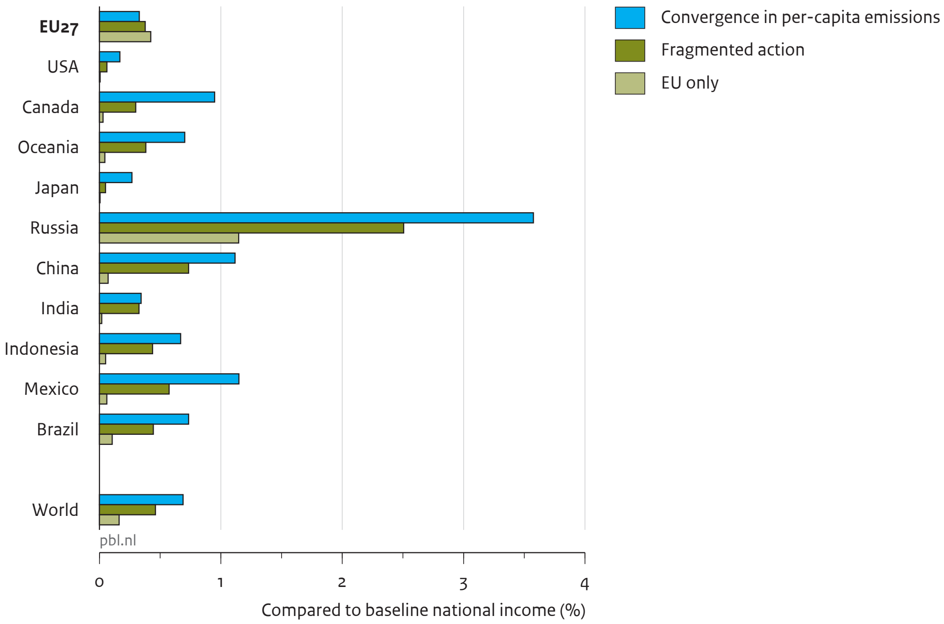
What are the expected carbon leakage and economic effects if the EU decides to unilaterally implement the 40% target? What are the effects if all other countries are less ambitious than the EU? (Chapter 5)

To analyse the carbon leakage and economic effects of EU unilateral action we included two scenarios. In both scenarios, the EU achieves its 40% reduction target by 2030. In one scenario, the rest of the world has no constraints on emissions (EU only). In the other scenario, the rest of the world reduces greenhouse gas emissions at levels of 50% of the reductions found in the *convergence in per-capita emissions* regime, except for the least developed regions (sub-Saharan Africa (excluding South Africa), South Asia and Southeast Asia (including India and Indonesia)) and the Middle East and northern Africa, which have no constraints on emissions (fragmented action).

Figure S.1 shows the welfare effects of these scenarios compared with a global action scenario based on convergence in per-capita emissions. Welfare losses in 2030 for the EU are projected to increase from 0.3% with global action to 0.4% with EU unilateral action, but the impact of unilateral action may be much larger for specific sectors, notable for the energy-intensive industrial sector. Welfare losses for the EU in the *convergence in per-capita emissions* regime are much lower than the world average, as is also the case with direct mitigation costs. Even in the fragmented action scenario, the projected welfare losses for the EU are slightly lower than the world average. Relatively high welfare losses were found for Russia, also for the EU only case, as the EU climate policy reduces imports from Russia – an important trading partner.

Through indirect effects of climate policies in the EU, emissions in the rest of the world may increase (carbon leakage). This may happen i) as a result of lower world energy prices as the demand for energy in the EU decreases, leading to a higher demand for energy in the rest of the world, and ii) as a result of industry relocating from the EU to other regions. In the EU only scenario, we project that for each Mt CO_2 eq reduction in the EU, an

Figure S.1
Welfare loss due to greenhouse gas reductions under 'fragmented action' and 'EU only' scenarios, 2030



Source: PBL WorldScan model.

Under the Fragmented action scenario, the EU achieves its 40% reduction target by 2030 and the rest of the world reduces greenhouse gas emissions at levels of 50% of the reductions found in the convergence in per-capita emissions *regime, except for the least developed regions and the Middle East and northern Africa, which have no constraint on emissions*

increase in emissions of 0.3 Mt CO_2 eq occurs in the rest of the world. The major part of this carbon leakage is not due to the relocation of industry, but to lower energy prices. This means that the amount of carbon leakage strongly depends on how a change in energy demand influences energy prices. In the fragmented action scenario, in which more than 70% of global greenhouse gas emissions are capped, carbon leakage is limited to 6%.

How can carbon leakage and welfare effects be mitigated? (Chapter 5)

Carbon border measures are often proposed as a way of protecting energy-intensive production sectors in countries with carbon costs against unfair competition from countries without carbon costs. To study the effect of such measures we imposed a levy on the import and a subsidy on the export of energy-intensive products at levels determined by the emissions associated with their production at the same price as faced by domestic producers.

Introducing border measures would have little effect, as they do not address the issue of decreasing energy prices – the main cause of carbon leakage. Therefore, border measures are not effective in reducing carbon leakage. Border measures do however reduce the decline in energy-intensive production in the EU as the burden to reduce emissions is shifted to other sectors.

What are the co-benefits of a 40% reduction in greenhouse gas emissions by 2030 for the EU? (Chapter 5)

Emissions of greenhouse gases and air pollutants originate to a large extent from the same sources, namely from fossil-fuel combustion and agricultural activities. A reduction in air pollution yields health benefits by reducing mortality. The projected reduction in deaths associated with exposure to air pollution is about 3.5% by 2030, compared with the baseline level, resulting from a 17% reduction in total SO_2, NO_x and particulate matter emissions, due to greenhouse gas mitigation, by 2030.

FULL RESULTS

ONE

Background and research questions

The long-term Dutch and European climate policy targets focus on limiting global temperature change to 2 °C above pre-industrial levels. As part of the Cancún Agreements (UNFCCC, 2011c), the EU has made an unconditional pledge to reduce greenhouse gas emissions by 20% compared with 1990 levels by 2020, and a conditional pledge of 30%, under the precondition that other developed countries commit to comparable emission reductions and that more advanced developing countries contribute adequately according to their responsibilities and respective capabilities. For 2050, there is 'an EU objective, in the context of necessary reductions according to the IPCC by developed countries as a group, to reduce emissions by 80–95% by 2050 compared to 1990', as agreed in October 2009 (Council of the European Union, 2009; European Parliament, 2009) and reaffirmed by the European Council in February 2011.

Some other developed countries have also announced long-term reduction targets (mainly for 2050, see www.climateactiontracker.org). For example, the United States announced a 42% emission reduction by 2030, compared with 2005 levels, in its Copenhagen Accord submission, which was reconfirmed in 2011 (UNFCCC, 2011a). Australia has adopted a reduction target for 2050 of 60% below 2000 levels. Mexico is the only developing country that has adopted a target for 2050 of 50% below 2000 levels.

In the 'Roadmap for moving to a competitive low-carbon economy in 2050' (European Commission, 2011), the European Commission sets out a plan to meet the 80% long-term target. It provides emission pathways towards 80% reduction in domestic emissions by 2050, which show cost-effective reductions by 2030 between 40% and 44% below 1990 levels. However, the EU has not yet decided on a greenhouse gas emission reduction target for 2030, and this is still under discussion[1].

The Dutch Government has called for such a greenhouse gas emission reduction target for 2030. More specifically, it has proposed a conditional European greenhouse gas emission reduction target for 2030 of 40% below 1990 levels (Dutch Government, 2011). The conditions relate to adequate global action and the adequate safeguarding of the competitiveness of European industry. The adequacy of global action depends both on whether the 2 °C objective remains within reach and whether contributions made by other countries are reasonable compared with the EU 40% reduction target for 2030. Factors determining whether or not the contributions of other countries are reasonable include their level of development and emission reduction potential. A greater effort is expected from richer countries than from poorer countries, while countries with a similar level of development would have to make a similar effort.

To work out the conditions, a working group was established, including representatives of the Dutch Ministry of Foreign Affairs, Ministry of Economic Affairs, Agriculture and Innovation, Ministry of Finance and Ministry of Infrastructure and the Environment. This working group asked PBL a number of questions that should shed light on the conditions under which the EU could implement a greenhouse gas emission reduction target for 2030 of 40% below 1990 levels. PBL's integrated assessment modelling framework IMAGE/TIMER/FAIR and WorldScan (Annex A) was used for the analysis.

The research questions included:

- What are the expected trends in greenhouse gas emissions without climate policy for the largest economies up to 2030? (Chapter 2)
- What global emission level is needed by 2030 to keep the 2 °C target within reach? To what extent does the emission level in 2020 influence this level? (Chapter 3)
- What kind of emission reduction targets would other countries need to adopt according to different effort-sharing regimes if the EU sets an internal reduction target for 2030 of 40%? (Chapter 4)
  - Would this lead to higher costs for richer countries? (Chapter 5);
  - Would this lead to similar efforts/costs for countries with similar welfare levels? (Chapter 5);
  - Would this lead to countries profiting from climate policy, even if the benefits of reduced climate change are not taken into account? (Chapter 5);
  - How robust are the results for different assumptions about baseline and cost curves? (Chapter 6)
- What targets for 2030 for the EU and other countries, under a regime of *equal costs as a percentage of GDP*, would be consistent with the 2 °C target? (Chapter 4) How robust are these results? (Chapter 6)
- What are the expected carbon leakage and economic effects if the EU decides to implement the 40% target unilaterally? And what are the effects if all other countries are less ambitious than the EU? How can these effects be mitigated? (Chapter 5)
- What are the co-benefits of a 40% reduction in greenhouse gas emissions by 2030 for the EU? (Chapter 5)

Note

1 In June 2012, the EU Council had not yet reached full agreement, due to opposition from Poland. Other EU Member States supported the EU Council Presidency conclusions on a Roadmap for Moving to a Competitive Low-Carbon Economy in 2050, reading: 'The Danish Presidency of the Council (…) recognises its finding that the EU's gradual, cost-effective transition to a low-carbon economy in 2050 passes through indicative milestones for EU domestic greenhouse gas emission reductions of 40% by 2030, 60% by 2040 and 80% by 2050 compared to 1990 as the basis for further work on the action needed to make the transition in a gradual, cost-effective way.'

Trends in greenhouse gas emissions without climate policies

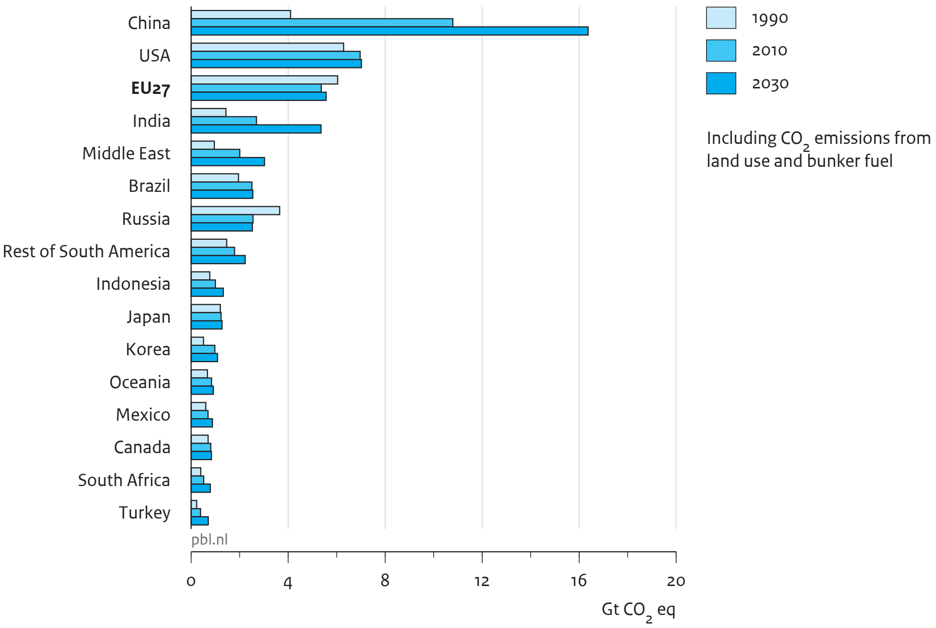
The expected trends in greenhouse gas emission levels are based on two sources. CO_2 emissions from land use, for instance, as a result of deforestation, are based on the IIASA forestry model G4M (Kindermann et al., 2008; Kindermann et al., 2006). All other Kyoto greenhouse gas emission levels are based on the baseline developed by PBL and used in the OECD Environmental Outlook to 2050 (OECD, 2012). For this study, the baseline data were harmonised to 1990–2005 emissions from several data sources (Annex A.1 provides more detailed information on the methodology and datasets used in the harmonisation procedure).

Both sources project emissions without future climate policies, which means that the pledges made in the Cancún Agreements are not taken into account. The main advantage of a baseline without climate policies is that all efforts to reduce greenhouse gas emissions are visible and that the costs of reducing greenhouse gas emissions include the costs of reaching the emission reduction targets of the 2020 pledges.

Based on the above two sources, Figure 2.1 shows the expected greenhouse gas emission levels by 2030, including CO_2 emissions from land use, for the 16 largest world regions in our model framework. The largest absolute increase in greenhouse gas emissions is expected for China and India, whereas emissions in most developed countries are projected to stabilise at 2010 levels. The projected global greenhouse gas emission level, including CO_2 from land use, is 62 Gt CO_2 eq for 2030, compared with 48 Gt CO_2 eq in 2010. Of the total 2030 emissions, 25% is expected to originate in China. China, the United States, the EU, India, the Middle East, Russia and Brazil, together, are expected to account for two thirds of global emissions by 2030 – which is the same share as in 2010. This share does not increase, as one might expect due to the strongly increasing emissions in China and India, because emissions in the United States, the EU and Russia are projected to remain more or less constant, while emissions in most other parts of the world are projected to increase strongly. The following sections of the report present results for the EU and for the countries with the highest baseline emissions in 2030.

The emission intensity (greenhouse gas emissions as share of GDP) of a country is an indication of the extent to which GDP depends on greenhouse gas emitting activities. A price on greenhouse gas emissions generally would more strongly affect countries with higher emission intensities. Figure 2.2 shows baseline emission intensities over time, relative to the global level. Emission intensities are expected to differ strongly by 2030 in the baseline, although the differences are smaller than is currently the case. In general, developed countries have lower emission intensities than developing countries. This is because high-income countries generally have larger low-carbon sectors, such as the service sector, and make use of relatively efficient technologies. Poorer countries have relatively large carbon-intensive sectors, such as heavy manufacturing. The emission intensities

Figure 2.1
Greenhouse gas emissions in the baseline



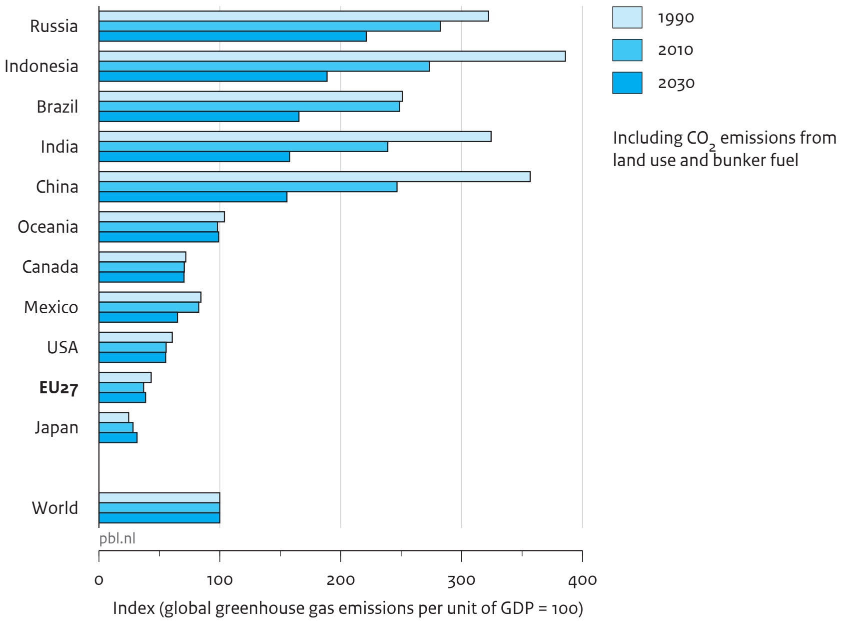
Source: Based on the OECD (2012) baseline but harmonised to 1990–2005 historical data (see Annex A.1) and including data on CO_2 emissions from land use from the IIASA forestry model G4M.

shown are based on GDP figures measured in market exchange rates (MER); if GDP measured in Purchasing Power Parity were to be used, the differences between developing and industrialised countries would be smaller by almost a factor of two.

The emission intensity of the EU is expected to decrease by about 33% between 2010 and 2030 in the baseline – compared with a global reduction of 35%. The lowest emission intensity by 2030 is expected in Japan, followed by the EU. The projected emission intensity of the United States is about 40% higher than that of the EU. For Canada, it is 80% higher and for Oceania, the emission intensity by 2030 is projected at more than 2.5 times the level of the EU. The highest emission intensities are found in Russia, Indonesia, Brazil, India and China – all of which have projected emission intensities of more than four times the level of the EU by 2030 (with GDP measured in MER).

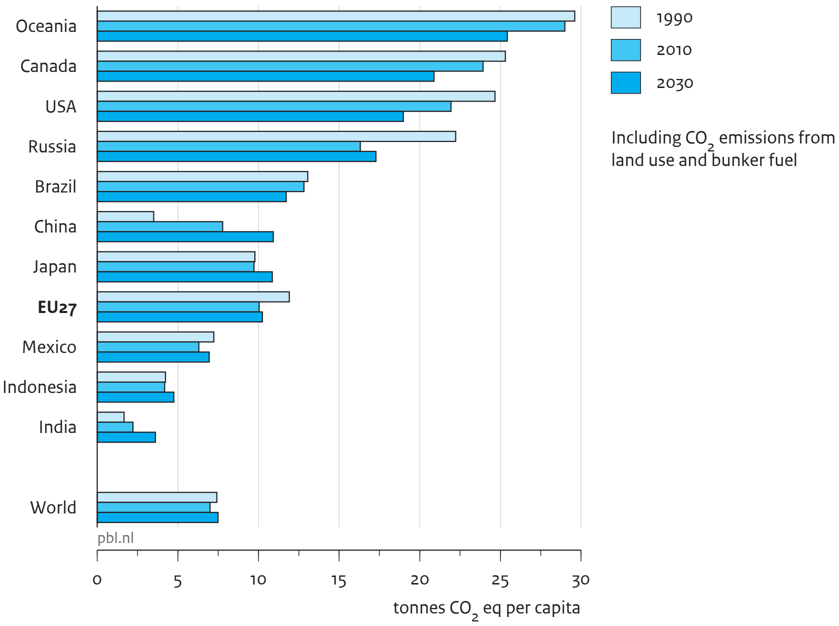
Another important indicator for comparing relative greenhouse gas emission levels between countries is per-capita emissions. Figure 2.3 shows that the highest levels for this indicator are expected in Oceania, Canada, the United States and Russia. For these countries, projections of per-capita emission levels range from 17 to 25 t CO_2 eq in 2030, compared with expected levels of 10 t CO_2 eq for the EU and less than 5 t CO_2 eq for India and Indonesia.

Figure 2.2
Emission intensities in the baseline



Source: Based on the OECD (2012) baseline but harmonised to 1990–2005 historical data (see Annex A.1) and including data on CO_2 from land use from the IIASA forestry model G4M. Emission intensities are based on GDP measured in market exchange rates.

Figure 2.3
Per-capita greenhouse gas emissions in the baseline



Source: Based on the OECD (2012) baseline but harmonised to 1990–2005 historical data (see Annex A.1) and including data on CO_2 from land use from the IIASA forestry model G4M.

THREE

Which global emission level by 2030 would be consistent with achieving the 2 °C target?

A good indicator of the likelihood of limiting global temperature change to 2 °C above pre-industrial levels is the total in cumulative emissions over the 21st century (Allen et al., 2009; Meinshausen et al., 2009). Many studies have analysed emission pathways that would restrict cumulative emissions to such levels to have a medium or likely chance of limiting global warming to 2 °C. These studies have been summarised in the UNEP emission gap reports (UNEP, 2010, 2011) and Rogelj et al. (2011) and came up with a 2030 emission level ranging from 32 to 44 Gt CO_2 eq for a medium likelihood (50% to 66%) of achieving the 2 °C climate goal. The range became 25 to 42 Gt CO_2 eq in 2030 for a likely (more than 66%) chance of achieving the 2 °C climate goal. However, these studies did not restrict 2020 emission levels and technology availability, and they assumed the full participation of all countries in emission reduction from 2010 onwards. In reality, the global emission level in 2030 consistent with 2 °C pathways depends, among other things, on assumptions regarding the availability and implementation of future emission reduction technologies and on the extent to which emissions are reduced in the short term.

3.1 Technology assumptions

There are several options that could result in a net removal of CO_2 from the atmosphere. These include reforestation and the use of bio-energy combined with carbon capture and storage (BECCS). The question of whether such technologies (BECCS in particular) could be used on a large scale in the long term plays an important role in determining shorter term emission reduction targets. If such technologies were to be applied in the long term, this would allow for higher emission levels early in the century. The use of BECCS not only depends on the physical potential for applying carbon capture and storage and biofuels (each with its own uncertainties), but also on the societal acceptance of these technologies (Johnsson et al., 2010).

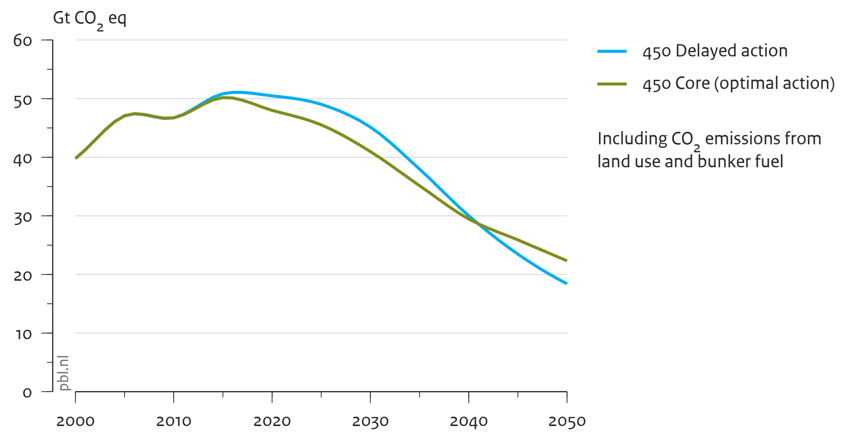
In this study, we have assumed that BECCS will become available and will be widely applied later in the century. Without BECCS, it would become very difficult in our model to maintain a reasonable chance of limiting global warming to 2 °C, especially when taking into account the greenhouse gas emission reductions pledged for 2020 (Van Vliet et al., 2012).

3.2 Assumptions on short-term emission reductions

With regard to short-term emission reductions, the greenhouse gas emission reductions pledged for 2020 as put forward by countries in the Cancún Agreements are important. The starting point of the analysis in this study was the implementation of a low pledge scenario by 2020. For most countries, these are unconditional pledges. However, for countries that have made a

Figuur 3.1

Greenhouse gas emission pathways for 450 ppm CO_2 eq



Source: OECD Environmental Outlook to 2050 (2012)

conditional pledge only, such as Canada, Japan and the United States, we have assumed that this pledge holds, which is similar to what is assumed by the UNFCCC (2011b). The calculated emission levels resulting from the submitted pledges and mitigation action plans for the developed and developing countries were calculated based on Den Elzen et al. (2012; also see Annex B).

Studies that optimise emission pathways for 2 °C from 2010 to 2100 find lower emission levels by 2020 than those analysing pathways based on the pledges (OECD, 2012; Van Vliet et al., 2012). The OECD Environmental Outlook to 2050 (OECD, 2012) analyses different emission pathways that stabilise greenhouse gas concentrations at 450 ppm CO_2 eq, which would give a chance of 40% to 60% of limiting global temperature change to 2 °C (Meinshausen et al., 2006; Meinshausen et al., 2009). These pathways were created by the same model framework as used in this analysis. One of these pathways, 450 Delayed Action, assumes an emission level for 2020 of 50.3 Gt CO_2 eq, as a result of the pledges. Another pathway, 450 Core, optimises the timing of emission reductions from 2010 onwards, which would lead to an emission level of 48.1 Gt CO_2 eq by 2020. In the third pathway, 450 Accelerated Action, early action is taken, leading to a global emission level of 46.2 Gt CO_2 eq by 2020. To arrive at the same greenhouse gas concentration goal, emissions in the 450 Delayed Action pathway would have to be reduced faster after 2020 compared with under the pathways 450 Core and 450 Accelerated Action. However, this can only be realised later in the century, due to inertia in the energy system.

For instance, delayed action would lead to more coal-fired power plants being built up to 2020, which creates a lock-in effect (the OECD Environmental Outlook assumes – as this study does for calculating costs – that newly built power plants are not immediately replaced with low-carbon alternatives, but will continue to be used for another 40 years). Therefore, higher emission levels by 2020 also imply higher levels by 2030. Not until 2040 will emission levels in the 450 Delayed Action pathway drop below those of the 450 Core pathway (Figure 3.1).

The OECD Environmental Outlook to 2050 is one of the very few studies to include an emission pathway consistent with the 2 °C target which starts in 2020 at an emission level resulting from the pledges. This pathway leads to a global emission level of 45.1 Gt CO_2 eq in the OECD 450 Delayed Action scenario, compared with 41 Gt CO_2 eq in the 450 Core scenario and 38.1 Gt CO_2 eq in the 450 Accelerated Action scenario. As this study used the same model framework as was used to create these emission pathways, the assumption has been made that the emission level consistent with 2 °C lies between 38.1 and 45.1 Gt CO_2 eq by 2030. It should be kept in mind, however, that the high end of this range implies higher costs throughout the century and a higher dependence on future technological developments, compared with a scenario with lower 2020 emission levels.

FOUR

Effort-sharing and reduction targets

This chapter explores the types of emission reduction targets the major economies would face under different effort-sharing regimes. The analysis takes a slightly different approach to common effort-sharing analyses (Figure 4.1). Usually, effort-sharing approaches start from a global emission target or emission reduction target, after which emissions (or emission reductions) are allocated according to a certain principle. In this analysis, the starting point is the 40% emission reduction target to be achieved within the EU by 2030. Based on this EU target, emissions or emission reductions were allocated to other regions according to several effort-sharing regimes. This implies that the global emission level is an outcome, not the starting point, of the analysis. Therefore, this chapter also deals with the question whether the global emission level in 2030 resulting from the effort-sharing regimes is consistent with an emission pathway that limits global warming to 2 °C.

4.1 Assumptions for emission reductions by 2020

The effort-sharing regimes start in 2020 from the level of a low-pledge scenario. In this scenario, the EU reduces its greenhouse gas emissions by 20% and all other regions implement their least ambitious pledge (if countries only have one conditional pledge, they implement that pledge – see Annex B). As the reductions resulting from the pledges influence the targets for 2030 that would be required to keep the 2 °C target within reach, Figure 4.2 shows by how much emissions would need to be reduced relative to our baseline emission levels. The pledges lead to relatively large reductions in emissions relative to the baseline for Japan, Oceania, Canada and Mexico. For Russia, India and Indonesia, the pledges are not expected to lead to emission reductions, relative to our baseline.

4.2 Description of effort-sharing regimes

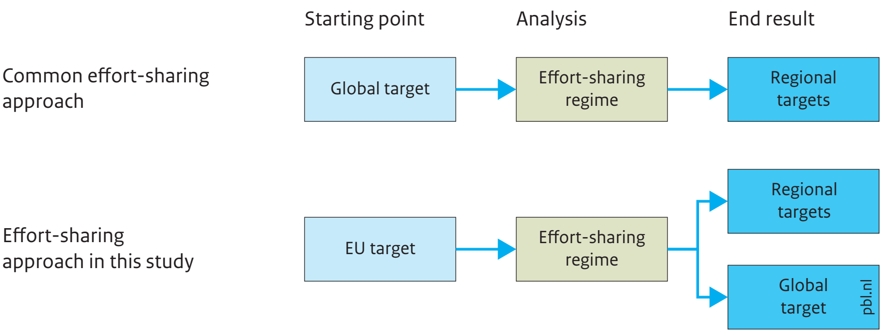
Given the proposed EU 40% emission reduction target for 2030, emission reductions or limitations for the other world regions were calculated based on three regimes, all differentiated according to economic development:

1. convergence in per-capita emissions by 2050 or 2055;
2. equal carbon tax by 2030;
3. equal mitigation costs as percentage of GDP by 2030.

Convergence in per-capita emissions

Under this regime, based on the work by Höhne et al. (2006), per-capita emission allowances of countries converge over time. In this study, we assumed convergence between 2020 and 2050 for all but the least developed countries. In the least developed countries (sub-Saharan Africa (excluding South Africa), South Asia and Southeast Asia (including India and Indonesia)), we assumed convergence between 2025 and 2055. Until 2025, the least developed countries can follow baseline

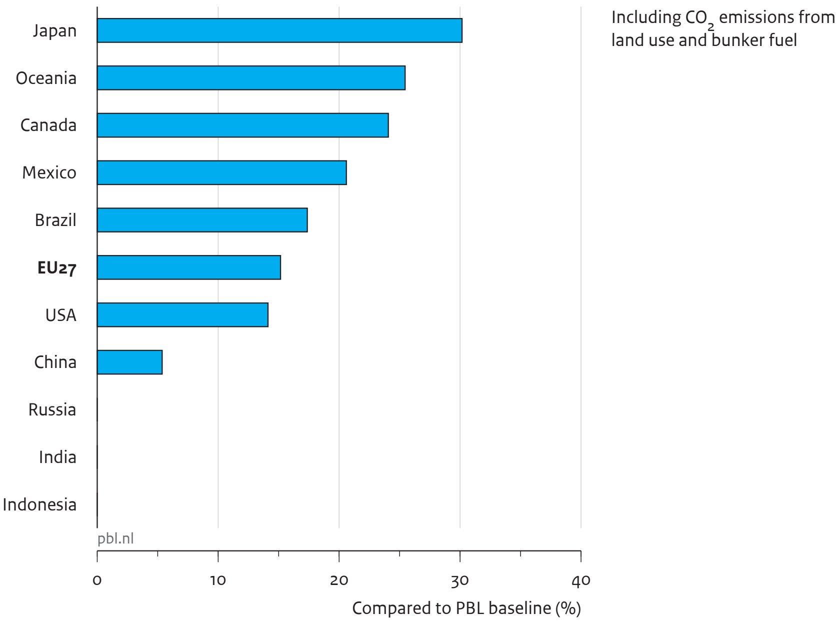
Figure 4.1
Effort-sharing approach used in this study



Source: PBL

The integrated modelling framework FAIR was used for the analysis. This model uses information on the potential and costs of reducing greenhouse gas emissions from the energy model TIMER, the land-use model IMAGE and the forestry model G4M. To analyse the uncertainty in results, we included an analysis with abatement cost curves from the POLES energy model (see Chapter 6).

Figure 4.2
Greenhouse gas emission reductions resulting from pledges, 2020



Source: Based on Den Elzen et al. (2012) and PBL FAIR/IMAGE/TIMER model calculations. The pledges by Russia, India and China are projected not to lead to reductions relative to our baseline. For Japan, a 25% reduction relative to 1990 levels is assumed, although there are indications that Japan will set a new, less ambitious target (Masaki, 2012).

emissions. The level of per-capita emissions to which all countries are assumed to converge by 2050 or 2055 is 2.3 tonnes CO_2 eq, while the starting levels in 2020 were determined from the pledges. The convergence level was calculated by assuming a linear decreasing trend in EU per-capita emissions towards 2050, consistent with a 20% target in 2020 and a 40% target by 2030. For 2050, such a regime would lead to a reduction in the EU of about 80% in 2050. All regions were required to reach their 2030 emission reduction targets through domestic emission reduction (no purchasing of emission credits was allowed). Only Canada, the Middle East, Japan and Oceania were allowed to achieve a maximum of 5% of their reduction relative to the baseline by buying emission credits – otherwise these regions would not be able to achieve their 2030 targets according to the reduction potential assumed in our model.

Equal carbon tax

Under this regime, marginal costs converge from their 2020 pledge levels to a common level in 2030 in all countries except for those that are least developed. Based on Figure 10 of the EU roadmap (European Commission, 2011), we assumed that the least developed regions converge to a marginal cost level of 30% of the common level. This common level was determined using the expected marginal costs for reaching the EU target of 40% domestic greenhouse gas emission reduction. In our model, these costs amount to USD 80/t CO_2 eq. For a comparable emission reduction level, the EU roadmap (European Commission, 2011) found marginal costs of USD 60/t CO_2 eq. One reason for the higher costs found in this study could be that we assumed lower emission reductions by 2020 (20% below 1990 levels) than the EU Roadmap (25% below 1990 levels). As higher short-term emission reductions decrease future costs by avoiding lock-in effects and learning-by-doing, the difference in emission reductions by 2020 could partly explain the difference in marginal costs by 2030 found between the EU Roadmap and this study. In fact, starting from the EU 30% high pledge in 2020 would decrease the marginal costs in 2030 for achieving the 40% target to USD 60/t CO_2 eq. Another reason is that greenhouse gas emissions decline more strongly in the EU roadmap baseline than in our baseline, which makes it cheaper to reach a certain target in the EU Roadmap study.

Equal relative costs

This regime is similar to the *equal carbon tax* regime, but instead of marginal costs, costs as share of GDP converge from their 2020 pledge levels to a common level in 2030. The common level was again determined using the expected direct cost of achieving the EU 40% domestic greenhouse gas emission reduction target, which would be 0.25% of GDP by 2030 according to our model. The least developed regions were also assumed to converge to a cost level of 30% of the level of other regions in this regime.

4.3 Equity principles

The above regimes are each based on different fairness principles (Text Box 1). The idea behind convergence in per-capita emissions is that each person has the right to an equal amount of emissions. It also takes into account current emission levels by allocating emission rights to nations based on their emissions per-capita levels in the starting year of the regime. In the convergence year, emission allowances are allocated in such a way that each country has the same per-capita emission allowances. Therefore, this approach is a combination of the egalitarian, sovereignty and acquired-rights principles.

A carbon tax is based on the responsibility principle: the impact of a carbon tax is high for countries with high emission levels or with a large potential to reduce emissions (Hof et al., 2009). A carbon tax has the advantage that, in a perfect world, emissions are reduced wherever it is cheapest to do so. However, as the burden of a carbon tax tends to fall on those regions with high emission intensities or with a large potential to reduce emissions, less developed countries are in general affected more than developed countries. Moreover, a carbon tax only takes into account current responsibility; if historical responsibility were to be taken into account less developed countries would in general be allocated more emission rights. To reduce the burden on the least developed regions, the carbon tax on these regions was set at 30% of the other regions (based on European Commission, 2011).

The allocation of emissions according to *equal relative costs* is based on the capability principle. Compared with *convergence in per-capita emissions*, it better takes into account the fact that some regions have less potential for reducing emissions and therefore should have less stringent targets.

4.4 Emission reduction targets

Table 4.1 (and Annex C in more detail) shows the emission reduction targets resulting from the three regimes. All the targets include the option to reduce CO_2 emissions by land-use measures such as reducing deforestation (see Text Box 2). An interesting observation is that all countries have the lowest reduction target in the *equal relative costs* regime. This is the result of the relatively low projected costs for the EU to achieve its 40% target

Text Box 1. Equity principles

A typology of four key equity principles was developed by Den Elzen et al. (2003) to characterise the various differentiation approaches of post-2012 commitments proposed in the literature and international climate negotiations:

(1) Egalitarian: all human beings have equal rights in the 'use' of the atmosphere.

(2) Sovereignty and acquired rights: all countries have a right to use the atmosphere and current emissions constitute a 'status quo right'.

(3) Responsibility/polluter pays: the greater the contribution to the problem, the greater the share of the user in the mitigation/economic burden.

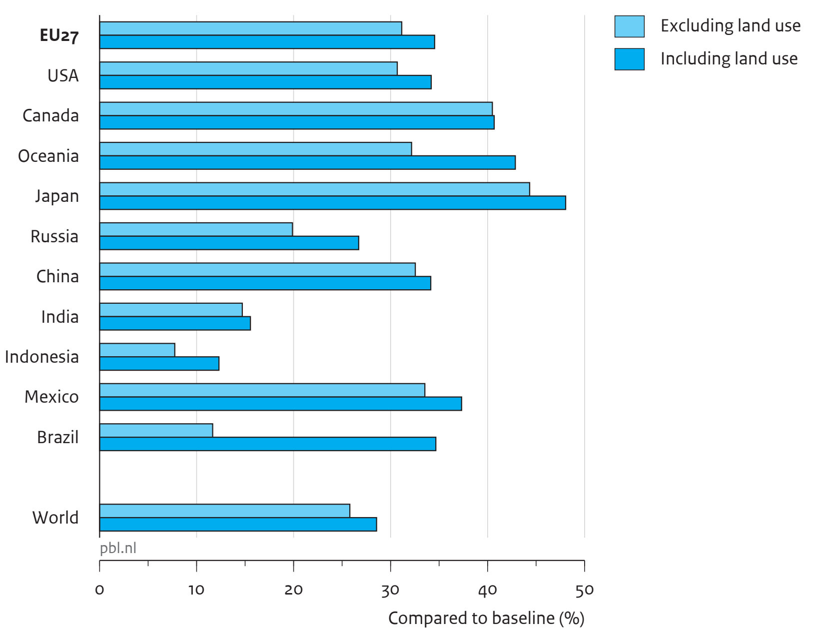
(4) Capability: the greater the capacity to act or ability to pay, the greater the share in the mitigation/economic burden. Capability, here, refers to countries' ability to pay as well as to their mitigation opportunities. Mitigation opportunities are not identical to mitigation capabilities: while a country may possess many opportunities for taking relatively cost-effective abatement measures, its actual capability to take these measures may be severely limited due to technological, institutional and/or financial constraints

Text Box 2. Reducing CO_2 emissions from land use

Activities to reduce CO_2 emissions from land use – afforestation, reforestation, forest management and reducing deforestation – can be used to help achieve the emission reduction targets. For 2030, we assumed that the potential for reducing CO_2 emissions from land-use activities will be fully used, both for developed and developing regions. As this potential is often less expensive than reducing emissions in other sectors, the relative reductions outside land-use activities are generally smaller than the targets given in Table 4.1. Figure 4.3 compares the total targets of the *convergence in per-capita emissions* regime with the reductions achieved outside the land-use sector. For all regions, but especially for Brazil, Indonesia, Oceania and Russia, CO_2 emissions from land use are reduced more than the average reductions in all sectors.

Figure 4.3

Greenhouse gas emission reductions under the 'convergence in per-capita emissions' regime, 2030



Source: PBL FAIR/IMAGE/TIMER model calculations.

As the targets for 2030 include CO_2 emissions from land use, credits or debits for reducing these emissions are not relevant after 2020. For achieving the pledges for 2020, we assumed that developed countries are granted the minimum number of land-use credits or debits according to Grassi et al. (2012), except for Canada, the United States and Oceania (see Annex A.2 for details). Finally, we assumed that the EU does not use land-use credits to achieve the 20% reduction pledge for 2020.

Table 4.1
Emission reduction targets for 2030 for different effort-sharing regimes and a 40% greenhouse gas emission reduction target below 1990 levels for the EU

	Convergence in per-capita emissions (%)			Equal carbon tax (%)			Equal relative costs (%)		
Relative to:	baseline	1990	2010	baseline	1990	2010	baseline	1990	2010
EU	-35	-40	-32	-35	-40	-32	-35	-40	-32
USA	-35	-27	-34	-38	-31	-37	-33	-25	-32
Canada	-41	-30	-39	-31	-17	-29	-26	-12	-24
Oceania	-43	-22	-27	-33	-8	-14	-28	-1	-8
Japan	-48	-45	-41	-40	-36	-31	-38	-34	-29
Russia	-27	-49	-28	-22	-46	-23	-14	-41	-15
China	-34	+163	0	-27	+191	+11	-19	+225	+24
India	-16	+215	+68	-17	+210	+65	-13	+223	+72
Indonesia	-12	+51	+16	-21	+35	+4	-12	+52	+17
Mexico	-37	-9	-21	-35	-6	-18	-30	+2	-12
Brazil	-35	-15	-34	-49	-34	-48	-32	-11	-30
World	-29	+13	-8	-28	+14	-6	-22	+24	+1

Source: PBL FAIR/IMAGE/TIMER model calculations

(0.25% of GDP). As all countries converge to the EU cost level, their associated reduction targets are relatively low.

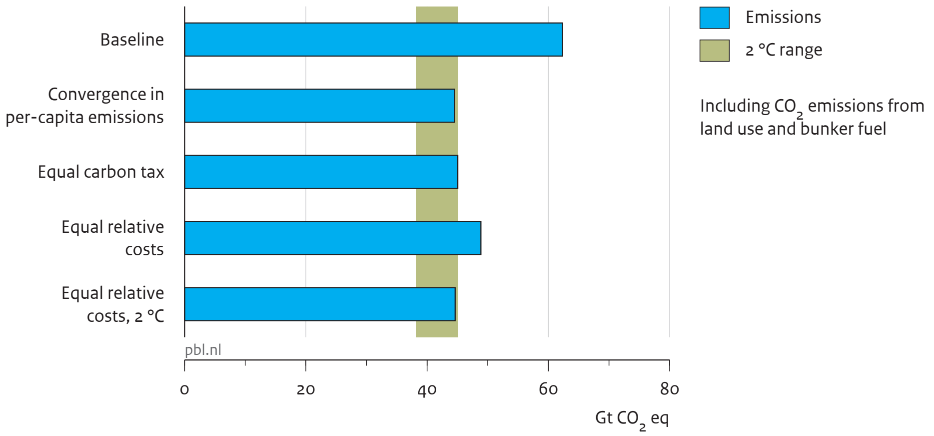
The main reason that a *convergence in per-capita emissions* regime leads to higher global reductions than an equal relative costs regime is that per-capita emissions of the EU are low compared with countries such as the United States, Canada, Russia and Oceania. As every country converges to the same per-capita emissions level, countries with high per-capita emissions need to reduce more to achieve their target, leading to higher total reductions.

An important reason why an *equal carbon tax* regime leads to higher reductions than an *equal relative costs* regime is that the EU is projected to have the second lowest emission intensity in 2030 (after Japan) in the baseline (Figure 2.2). Countries with high emission intensities, such as China, India, Indonesia and Brazil, show relatively high reductions under a carbon tax.

Figure 4.4 compares the expected 2030 global emission level in the baseline and the regimes with the range consistent with limiting temperature change to 2 °C according to the OECD Environmental Outlook (see Chapter 3). In the baseline, emissions are projected to be 18–24 Gt CO_2 eq above the emission range consistent with 2 °C. In the *convergence in per-capita emissions* and *equal carbon tax* regimes, the global emission levels are just within this range. As reductions in the *equal relative costs* regime are less than in the other regimes, the global emission level in this regime is higher and is still 4–10 Gt CO_2 eq above the range consistent with 2 °C. We therefore also added a scenario that leads to a global emission level in 2030 that is just within the range consistent with 2 °C with equal relative costs by 2030 (*equal relative costs, 2 °C*).

Table 4.2 shows the range of emission reduction targets resulting from the three default regimes (in which the EU has a reduction target of 40%), together with the *equal relative costs*, 2 °C regime. The reductions are given relative

Figure 4.4
Global greenhouse gas emissions, 2030



Source: PBL FAIR/IMAGE/TIMER model calculations and OECD (2012)

Table 4.2
Range of emission reduction targets, based on three regimes and a 40% greenhouse gas emission reduction target below 1990 levels for the EU, compared with an *equal relative costs*, 2 °C regime and announced targets

	Range based on regimes (%)	Equal relative costs, 2 °C (%)	Announced targets[1] (%)
Below 1990 levels:			
EU	40	47	41–45*
USA	25–31	37	33
Canada	12–30	22	14–18
Oceania	1–22	10	1*
Japan	34–45	45	36–43
Russia	41–49	44	33
Below baseline levels[2]:			
China	19–34	25	
India	13–17	19	
Indonesia	12–21	19	
Mexico	30–37	39	38*
Brazil	32–49	46	
World	22–29	28	

Source: PBL FAIR/IMAGE/TIMER model calculations and based on individual country assessments by http://climateactiontracker.org/.

[1] *Announced targets are either announced or adopted targets: adopted targets are denoted by a *. The United States is the only country that has announced a target for 2030. Other countries have announced long-term targets for 2050; for these countries the implied reductions for 2030 are shown here, assuming that the targets for 2050 are reached linearly between 2020 and 2050, based on UNFCCC data (submission 2010) taken from http://unfccc.int/ghg_data/ghg_data_unfccc/items/4146.php. The targets are excluding CO_2 emissions from land use. See Annex B for more detail on announced long-term targets.*

[2] *Emission reduction targets are expressed relative to 1990 emission levels for developed countries because the EU 40% target is expressed relative to 1990 levels as well. Emissions in developing countries generally show a strongly increasing trend (see Figure 1); therefore emission reductions are shown relative to projected baseline levels.*

to 1990 for developed countries and against baseline levels for developing countries. It should be noted that the low range of the targets – which are the targets resulting from the *equal relative costs* regime – lead to a global emission level by 2030 above the range consistent with 2 °C. The emission reduction targets of the United States, India and Mexico are relatively insensitive to the effort-sharing regime. For Canada, Oceania, China and Brazil, the range in emission reduction targets is relatively large. This is due to the much higher target for Canada, Oceania and China under the *convergence in per-capita emissions* regime and for Brazil under the *equal carbon tax* regime.

The table also shows that in the *equal relative costs*, 2 °C regime the 2030 target of the EU would be 47% instead of 40% below 1990 levels. The target of such a regime would lie outside the range of the three default regimes for the United States and India (and just outside the range for Mexico).

Some countries have announced long-term greenhouse gas emission reduction targets for the year 2030 or 2050 (Annex B). For these countries, the implied or adopted reduction targets for 2030 are also presented in Table 4.2. Interestingly, most implied or adopted emission reduction targets are within the range resulting from the combination of a 40% EU target with the effort-sharing regimes included in this study. The only exception is Russia, which announced a target of 50% below 1990 levels by 2050 (note that the 2010 emission level of Russia is about 30% lower than its 1990 emission level).

FIVE

Mitigation costs and welfare effects

This chapter provides the projected direct mitigation costs and welfare effects resulting from achieving the mitigation targets found in Chapter 4 (see Text Box 3 for the difference between direct mitigation costs and welfare effects and Annex A for a description of the methodology used to calculate mitigation costs and welfare effects). We also present welfare effects and carbon leakage resulting from simulations in which Europe unilaterally reduces emissions or other world regions reduce emissions to a lesser degree than the ranges found in the previous chapter.

5.1 Mitigation costs

Table 5.1 shows the direct mitigation costs in 2030 resulting from the regimes. The projected cost of achieving the EU 40% target is about 0.25% of GDP in 2030. The costs in 2030 depend on how much emissions are reduced by in 2020. If the EU conditional high pledge of 30% reduction by 2020 were to be implemented, this would reduce the cost – due to learning-by-doing and avoiding lock-in effects – to 0.2% of GDP in 2030. The differences in costs between regimes and countries mainly reflect the differences in the emission reduction targets as shown in Table 4.1. As the emission intensities (including CO_2 emissions from land use) of Russia, China, India, Indonesia and Brazil are projected to be at least a factor of four higher than that of the EU (see Figure 2.2), these regions show high mitigation costs for the *equal carbon tax* regime compared with an *equal relative costs* regime.

The *convergence in per-capita emissions* regime shows the largest differences in costs between regions. For Russia and China, direct mitigation costs as a share of GDP are even a factor of six to seven higher than those of the EU in this regime. This outcome is a result of a regime based on per-capita emissions, not taking into account circumstances such as mitigation potential. This potential is limited for Russia due to the large overcapacity in historically-built coal-fired power plants, which prevents the building of new, low-carbon power plants. The potential for reducing emissions is also limited in China: China has expanded its energy sector considerably with coal power plants in the past decade, which makes replacement of or adjustments to these investments very expensive, so that it is more difficult for China to move to low-carbon technologies.

The global mitigation cost is higher in the *convergence in per-capita emissions* regime (0.7% of GDP in 2030) than in the *equal carbon tax* regime (0.4%), as in the latter regime emissions are reduced wherever it is cheapest to do so. The global mitigation cost is lower in the *equal relative costs* regime as global emission reductions are less (Figure 4.4). To reach similar reductions in the *equal relative costs* regime, mitigation costs would increase more than two-fold (allowing emission trading in such a scenario would somewhat reduce the costs, but would still lead to mitigation costs of close to 0.5% for the EU and for the

Table 5.1
Projected direct mitigation costs as share of GDP, 2030

	Convergence in per-capita emissions (%)	Equal carbon tax (%)	Equal relative costs (%)	Equal relative costs, 2°C (%)
EU	0.24	0.24	0.25	0.57
USA	0.29	0.39	0.25	0.58
Canada	1.03	0.39	0.25	0.58
Oceania	1.07	0.48	0.25	0.57
Japan	0.51	0.28	0.25	0.58
Russia	1.57	0.75	0.25	0.57
China	1.58	0.74	0.25	0.57
India	0.13	0.14	0.07	0.17
Indonesia	0.09	0.25	0.07	0.17
Mexico	0.51	0.40	0.25	0.57
Brazil	0.27	0.82	0.25	0.57
World	0.66	0.43	0.23	0.53

Source: PBL FAIR/IMAGE/TIMER model calculations

Text Box 3. Direct mitigation costs versus welfare effects
Different types of models were used to estimate the costs of climate policy. Partial equilibrium models, such as the FAIR model used for the mitigation cost calculations, focus on the competition between different technologies for meeting the demand for goods and services. Such models derive cost estimates from the detailed description of the energy and land-use systems. In contrast, general equilibrium models, such as the WorldScan model used for the welfare effect calculations, focus on the economy as a whole and the interactions between the various sectors. These models do not focus on direct costs, but on changes in economic production and consumption levels or welfare. Both types of models have their strengths and weaknesses. The direct mitigation costs calculated by partial equilibrium models can be determined relatively straightforwardly as a first order estimate of the investments required for mitigation, but neglect the fact that, by changing prices, indirect effects may occur in the economy. For instance, reducing emissions is likely to lead to a shift in consumption and production from carbon-intensive goods and services to those that are less carbon-intensive and reductions in fossil-fuel use will lead to losses in export revenues for fossil-fuel exporters.

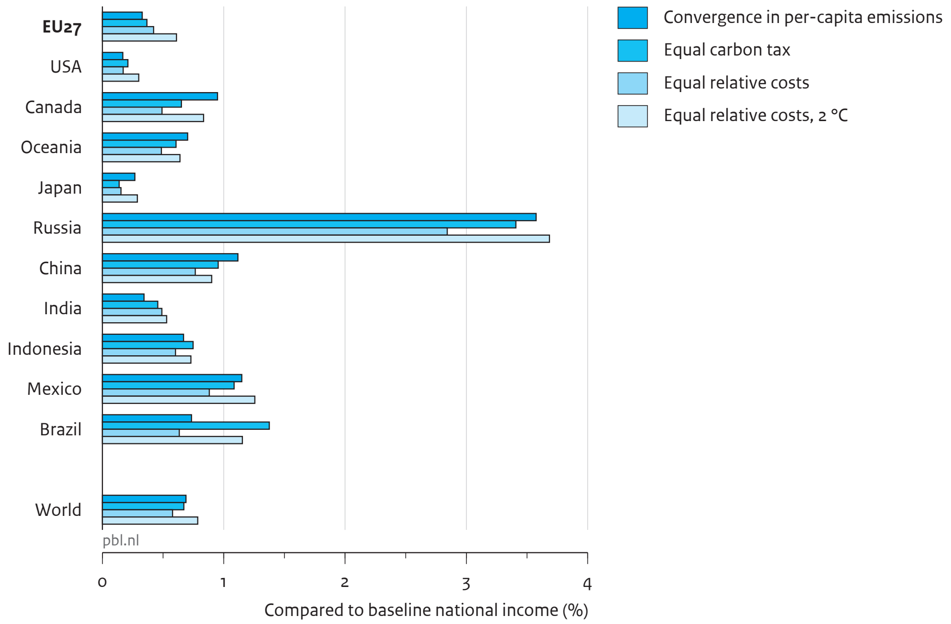
world as a whole). The strong increase in mitigation costs resulting from moving from a 40% to a 47% reduction in emissions indicates that, beyond 40%, emission reduction measures start to become increasingly expensive.

The reduction targets do not lead to higher costs for richer countries, for the reasons mentioned above. By definition, costs between countries are similar in an *equal relative costs* regime, but large differences in costs are found for the other regimes. As we have assumed that all targets are achieved through domestic emission reduction, we do not project that countries will profit from emissions trading. However, even if emissions trading were allowed, we project that the benefits of emissions trading would outweigh the costs of reducing emissions in almost none of the regions (only the least developed countries may have a very small net benefit resulting from the regimes).

5.2 Welfare effects, global action

Direct mitigation costs are an indication of the investments required to reduce greenhouse gas emissions. Direct cost calculations, however, do not account for the indirect effects that may occur through various propagation mechanisms in the economy. Analysing the indirect effects of climate policies requires a model with an economy-wide perspective, taking into

Figure 5.1
Welfare loss due to greenhouse gas reductions, 2030



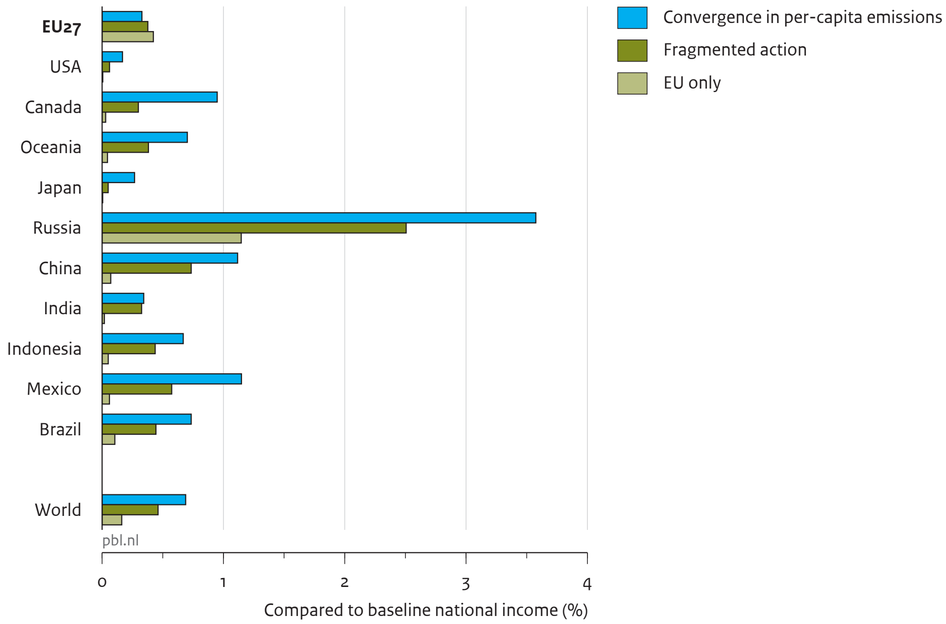
Source: WorldScan model calculations

account the effect of changes in one sector or region on economic activities in other sectors and regions. To analyse these macro-economic effects resulting from mitigation efforts in the different regimes, the computable general equilibrium model WorldScan was used (Annex A). As WorldScan does not include mitigation options for emissions from land use, the emission reductions imposed in WorldScan correspond to the emission reductions resulting from FAIR, but excluding the reductions projected by FAIR for emissions from land use. Figure 4.3 compares the total emission reductions with the emission reductions from land-use activities. Large differences were found, in particular for Brazil, and to a lesser degree for Oceania, Russia and Indonesia. In the FAIR results, these countries rely strongly on reducing land-use emissions to achieve their targets.

Figure 5.1 shows projected welfare losses in the regimes, measured relative to baseline national income levels. For the EU, the welfare loss of achieving the EU 40% target ranges from 0.3% to 0.4%, depending on the mitigation effort of other regions in the world. In general, welfare losses for the EU are smaller with higher reductions in other regions. This is because companies in the EU can remain more competitive (defined as the ability to maintain or increase market share) if other regions face higher costs to reduce emissions (see Section 5.3). The projected welfare loss of the EU in the *equal relative costs, 2 °C* regime, in which the EU reduces emissions by 47%, amounts to 0.6%.

Differences in welfare effects between regions result from differences in the reduction targets and differences in the costs of reducing greenhouse gas emissions, but also from different indirect impacts on the various economies. Welfare losses in the United States are smaller than in the EU for all regimes. The reason is that existing energy taxes are lower in the United States than in the EU, therefore the impact of a carbon tax on the economy is smaller. In Japan, welfare losses are relatively small as Japan, being a net importer of fossil fuels, takes advantage of decreasing fuel prices. On the other hand, welfare losses of fossil fuel exporting countries such as Russia are relatively large as their income from the export of fossil fuels declines.

Figure 5.2
Welfare loss due to greenhouse gas reductions under 'fragmented action' and 'EU only' scenarios, 2030



Source: WorldScan model calculations

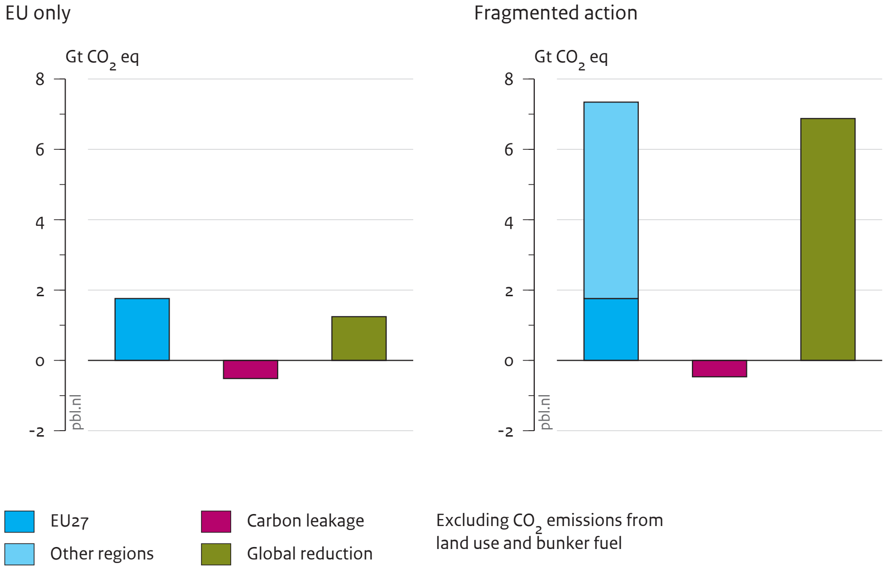
5.3 Welfare, competitiveness and carbon leakage effects, fragmented and EU unilateral action

The welfare losses presented in Section 5.2 are in the case of global action. In a more fragmented world, welfare losses for the EU might be different because the competitiveness of EU firms will be affected. Moreover, carbon leakage might also take place. To analyse the effects on welfare, carbon leakage and EU competitiveness in a world in which no global action is taken, we included two scenarios. In both scenarios, the EU achieves its 40% reduction target by 2030. As an extreme case, the rest of the world has no constraint on emissions in one scenario (EU only). In the other scenario, the rest of the world reduces greenhouse gas emissions at levels of 50% of the reductions found in the *convergence in per-capita emissions* regime, except for the least developed regions (sub-Saharan Africa (except South Africa), South Asia and Southeast Asia (including India and Indonesia)) and the Middle East and northern Africa, which have no constraints on emissions (fragmented action). In both these scenarios, global emission reductions fall way short of staying on a 2 °C emission pathway.

Welfare loss, fragmented and EU unilateral action
Figure 5.2 presents projected welfare losses for the *convergence in per-capita emissions* regime compared with simulations for the EU only and the fragmented action scenarios. The results show somewhat larger welfare losses for the EU in the case of unilateral action (0.4%) compared with global action (0.3%). This implies that, in terms of welfare loss, the risk of unilateral action, measured as the extra welfare loss if other countries reduce less, is relatively small. Another interesting finding is that Russia faces relatively large welfare losses, also in the EU only case, as the EU imports less energy from Russia, an important trading partner.

The EU Roadmap (European Commission, 2011) does not provide projections of welfare losses, but reports changes in GDP, which is a measure of overall economic activity. In a fragmented action scenario, in which the emissions of other countries remain constant after 2020 at their pledges level, GDP in 2030 is reduced by about 0.8% compared with the baseline. For a comparable scenario, WorldScan found a 0.7% loss in GDP. Although related, changes in GDP do not directly correspond to changes in social welfare. Welfare effects reflect changes in the

Figure 5.3
Greenhouse gas reductions, 2030



Source: WorldScan model calculations

utility households derive from the consumption of goods and services. This relates to changes in income and hence to changes in GDP. Changes in relative prices, for example through terms-of-trade effects, may however cause significant differences between welfare effects and changes in production and consumption.

Carbon leakage effects, fragmented and EU unilateral action

Emissions in the rest of the world may increase due to the indirect effects of climate policies in the EU. This may happen i) as a result of lower world energy prices, as the demand for energy in the EU decreases, leading to a higher demand for energy in the rest of the world; and ii) as a result of industry relocating from the EU to other regions. In our model, this carbon leakage rate amounts to almost 30% in the EU only regime (Figure 5.3), implying that for each Mt CO_2 eq reduction in the EU, an increase in emissions of 0.3 Mt CO_2 eq is projected to occur in the rest of the world (a similar result was found by Bollen et al., 2012). In the fragmented action scenario, in which more than 70% of global greenhouse gas emissions are capped and carbon leakage is only possible in a few regions with relatively small economies, the leakage rate is reduced to 6%. The most important reason for this carbon leakage is that the decrease in demand for energy in the EU leads to lower world energy prices. If this fossil-fuel price channel of carbon leakage is excluded in the model calculations, carbon leakage in the EU only case reduces to 8%, which can be attributed to the relocation of EU production.

Competitiveness effects, fragmented and EU unilateral action

In the global action *convergence in per-capita emissions* regime, European industry will gain market share (Figure 5.4). However, in the fragmented action and EU only scenarios, the energy-intensive industry sector in particular is projected to lose market share. Carbon border measures are often proposed as a way of protecting energy-intensive industry in countries with carbon costs against unfair competition from countries without carbon costs (Bollen et al., 2011). To study the effect of such measures, we imposed a carbon levy on emissions embodied in EU imports of energy-intensive products, and applied carbon refunds on exports of energy-intensive sectors in the EU. The level of these border measures was based on the average prevailing direct and indirect carbon costs in domestic production of the energy-intensive sectors.

In our model, the introduction of border measures hardly affects carbon leakage in the EU only and the fragmented action cases as border measures do not affect fossil fuel prices, which are the main cause for the overall carbon leakage. However, border measures do reduce the relocation of energy-intensive production from the EU to other regions. Figure 5.4 shows that this is due to a shift in the burden of reducing emissions to other sectors. Figure 5.4 also indicates that the output of the services sector, which in the baseline is responsible for 75% of total GDP by 2030, increases in the various cases, while

Figure 5.4

The effects on competitiveness, 2030

Source: WorldScan model calculations

output levels of the industry sectors decrease. This is the result of a shift in the economy from greenhouse gas-intensive production to the services sector, which is less greenhouse-gas-intensive, as a result of changing relative prices. Moreover, in the EU only and the fragmented action scenarios, the industry sectors also face a loss of competitiveness, represented by a reduction in the share of world production. Employment in the industry sectors decreases by about 1%, though this is compensated to a large extent by increasing employment in the service sector. Annex D presents more detailed results on sectoral effects.

5.4 Co-benefits of the EU 40% reduction target

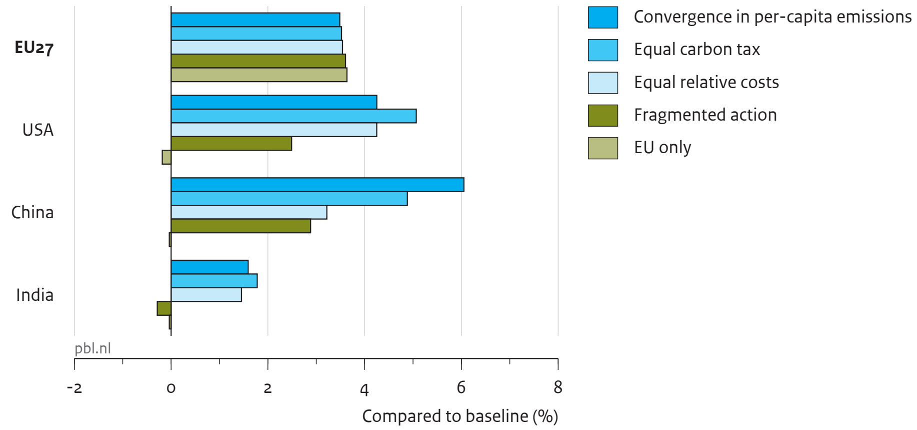
Air pollution

Emissions of greenhouse gases and air pollutants largely originate from the same sources: fossil fuel combustion and agricultural activities. The mitigation of greenhouse gas emissions reduces air pollution, mainly due to a reduction in the emissions of SO_2, NO_x and particulate matter. This is the result of a reduction in fossil fuel use due to energy efficiency improvements, a shift to renewable energy sources and changes in the sectoral structure of the economy. For the EU, the projected reduction in total SO_2, NO_x and particulate matter emissions resulting from the 40% reduction target is 17% by 2030. A reduction in air pollution yields health benefits by reducing mortality. In the baseline, which does not include new air pollution policy but does include policies that were in existence by 2010, the number of premature deaths projected for the EU is about 68,000 by 2030. Figure 5.5 presents the estimated reduction in deaths associated with air pollution, compared with this baseline. For the EU, the reduction in deaths is projected at about 3.5%, exclusively as a co-benefit of greenhouse gas mitigation (for details on the methodology used for this analysis, see OECD, 2012). When compared with Table 4.1, Figure 5.5 shows that the reduction in deaths in other countries increases with increasing greenhouse gas emission reductions.

Energy security

Promoting greater energy security is one of the objectives of the EU Roadmap. Energy security is a complex issue and has various economic and political dimensions. It is beyond the scope of this study to deal with these extensively. An indicator often used to analyse effects of policies on energy security is fuel import dependency,

Figure 5.5
Reduction in premature deaths associated with exposure to air pollution, 2030



Source: WorldScan model calculations, in accordance with the methodology applied in OECD (2012, Section 6)

defined as total net imports of fossil fuels as a share of primary energy consumption. Fuel import dependency in the EU is currently about 55%. According to our model projections, the EU 40% target will reduce fuel import dependency by 2% at the most, even though the import of fossil fuels will decrease strongly. An important reason for the small reduction in fuel import dependency is that primary energy consumption also decreases strongly. In all scenarios, total primary energy consumption per unit of GDP is reduced by 15% to 16% in the EU as a result of energy efficiency improvements. Such a reduction in primary energy consumption reduces the fossil fuel dependency in the EU, which makes the EU less vulnerable to changes in fossil fuel prices and oil shocks (Darmstadter, 2006).

SIX

Robustness of results

Two large sources of uncertainty are the cost curves and the baseline used in the model. To assess the effect of this uncertainty on our results, we evaluated the effort-sharing regimes using a different set of cost curves and corresponding baseline projections (from the energy system model POLES, see Annex A)[1]. In this section, baseline emissions, emission reduction targets and mitigation costs resulting from calculations using TIMER/FAIR data are compared with results from calculations using POLES data. This exercise does not provide the full range of uncertainty (for which more model runs, using different model frameworks, would be necessary), but indicates how a different set of cost curves could influence the results. Section 6.1 looks at the robustness of reduction targets for the effort-sharing regimes (and Table 6.1 specifically at the robustness of the range of targets), Section 6.2 at the robustness of the targets in the *equal relative costs*, 2 °C regime and Section 6.3 at the robustness of the mitigation costs.

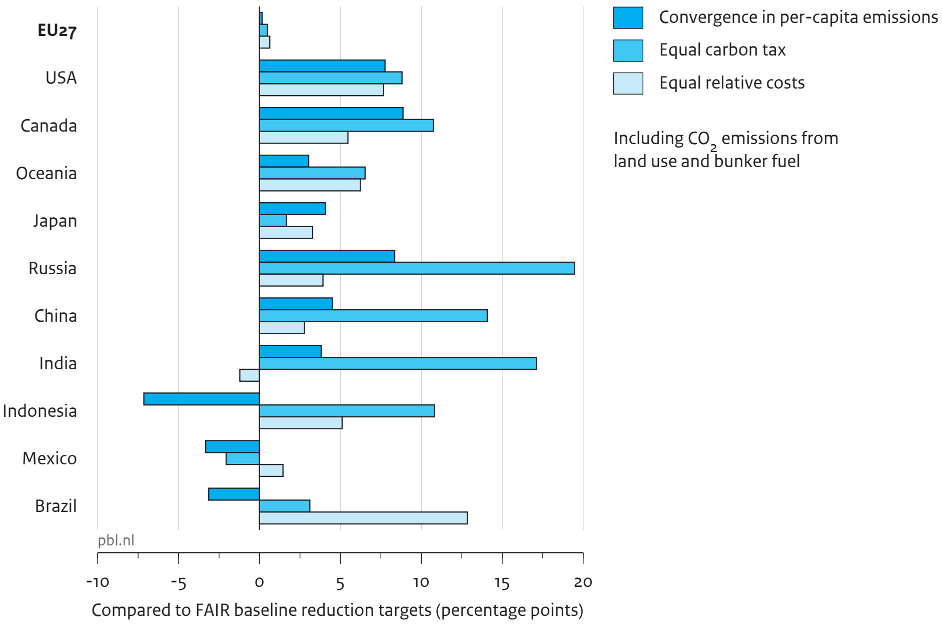
6.1 Reduction targets based on the EU 40% target

Differences in results between POLES and FAIR cost curves are partly due to differences in mitigation potential and partly to differences in baseline projections. Figure 6.1 compares the emission reductions, relative to baseline projections, resulting from the effort-sharing regimes between POLES and FAIR (absolute numbers are given in Table 6.1 and in Annex C). For the *convergence in per-capita emissions* regime, POLES projects higher emission reductions relative to the baseline for countries for which it also projects higher baseline emissions (Canada, Russia, United States, China, India and Oceania). The opposite is also true: lower emission reductions are projected for countries with lower baseline projections (Brazil, Mexico and Indonesia).

With an equal carbon tax, differences between FAIR and POLES are larger. In this regime, all regions (except Mexico) have higher reductions according to POLES than according to FAIR. The reason for this is that POLES is less optimistic about the abatement potential of Europe: with the POLES cost curves, a carbon price of USD 150/t CO_2 is needed to achieve the 40% target in 2030, compared with USD 80/t CO_2 with the FAIR cost curves (and about USD 60/t CO_2 in the Roadmap study of the European Commission). In general, POLES assumes relatively more potential in developing regions and less in developed regions than FAIR, at a given carbon price. This implies that with the POLES cost curves, all regions face a carbon tax almost twice as high as with the FAIR cost curves – which leads to higher reductions, especially in less developed regions. The reduction targets in the *equal relative costs* regime are higher for almost all regions as well, for the same reason (all regions face higher costs with the POLES than with the FAIR cost curves).

The POLES cost curves lead to a slightly lower global emission level in 2030 than the FAIR cost curves for the

Figure 6.1
POLES baseline reduction targets compared to FAIR, 2030



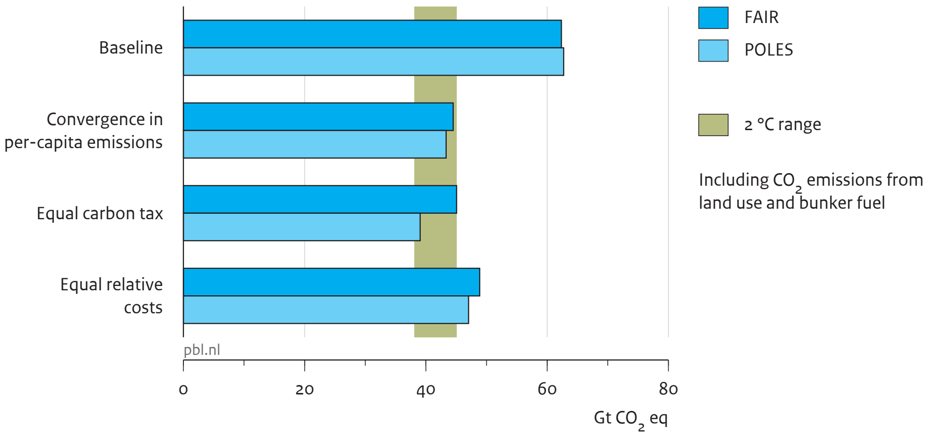
Source: PBL FAIR/IMAGE/TIMER model calculations and Enerdata (2010)

Table 6.1
Range of emission reduction targets, based on three regimes and a 40% greenhouse gas emission reduction target below 1990 levels for the EU, FAIR versus POLES

	FAIR (%)	POLES (%)
Below 1990 levels:		
EU	40	40
USA	25–31	24–32
Canada	12–30	2–28
Oceania	1–22	4–21
Japan	34–45	32–45
Russia	41–49	21–43
Below baseline levels:		
China	19–34	21–41
India	13–17	12–34
Indonesia	12–21	5–32
Mexico	30–37	32–34
Brazil	32–49	32–52
World	22–29	25–38

Source: PBL FAIR/IMAGE/TIMER model calculations and Enerdata (2010)

Figure 6.2
Global greenhouse gas emissions, 2030



Source: PBL FAIR/IMAGE/TIMER model calculations and Enerdata (2010)

convergence in per-capita emissions and *equal relative costs regimes*, and to a substantially lower level for the *equal carbon tax* regime (Figure 6.2). The lower global emission level for the *equal carbon tax* regime and *equal relative costs* regime can be explained by higher reductions in almost all regions, as explained above.

Table 6.1 shows whether the differences in reduction targets between POLES and FAIR resulting from the individual regimes affect the total range of targets found by the regimes, as given earlier in Table 4.2. Interestingly, POLES and FAIR have a very similar range for the United States, Oceania, Japan, Mexico and Brazil. For the first three countries, the reason is probably that even though POLES projects lower mitigation potential for all these countries, it also projects lower mitigation potential for the EU. This implies that the differences in cost curves between the countries are similar between FAIR and POLES. The reason for similar reduction targets for Mexico and Brazil could be that these countries rely strongly on reducing deforestation emissions, for which the same cost curves are used.

For Canada and Russia, the range of reduction targets relative to 1990 is both larger and lower according to POLES – even though reductions compared with the baseline were higher. The reason is that POLES uses a different historical dataset that gives lower emission levels for 1990 for these countries. The largest differences in the reduction range between FAIR and POLES are found for Indonesia, India and – to a lesser extent – China. For these countries, the range (especially the high end of the range) is much larger according to POLES. One of the most important reasons for this larger range is the much higher global carbon tax applied in the *equal carbon tax* regime.

6.2 Reduction targets for an *equal relative costs*, 2 °C regime

Section 6.1 showed how sensitive the targets are to a different set of cost curves and a different baseline. It is difficult to interpret the differences in targets resulting from the POLES and FAIR cost curves. This is due to the effort-sharing regimes being based on the EU 40% target. As higher costs are required with POLES to achieve the EU 40% target, all other regions also face higher costs in the *equal relative costs* and *equal carbon tax* regimes. Differences in targets are therefore partly caused by imposing higher costs or tax levels.

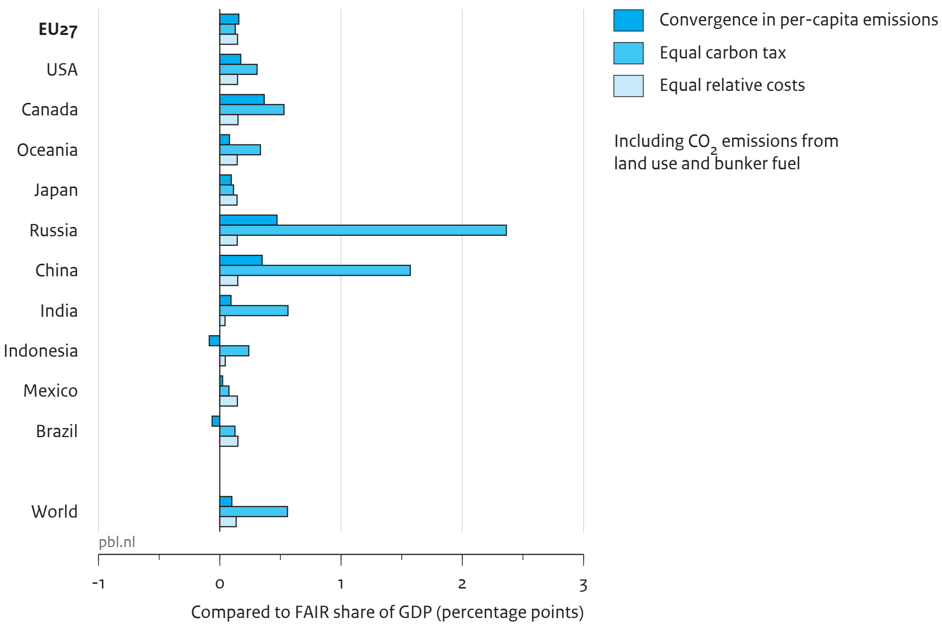
To better understand how differences in cost curves between countries influence emission reduction targets, Table 6.2 compares reduction targets between FAIR and POLES, according to an *equal relative costs* regime in which the global emission level is taken as the starting point (more specifically, the *equal relative costs*, 2 °C regime). Targets are shown relative to the baseline, as this is the best indicator of the required effort (note that 1990 emission levels differ between the POLES and FAIR datasets as we did not use harmonised data for POLES – see Annex A.1). The reductions for the EU are somewhat

Table 6.2
Comparison of reduction targets below baseline levels in the equal relative costs, 2 °C regime, FAIR and POLES cost curves

	FAIR (%)	POLES (%)
EU	43	41
USA	43	45
Canada	35	36
Oceania	34	37
Japan	48	45
Russia	19	22
China	25	25
India	19	15
Indonesia	19	22
Mexico	39	35
Brazil	46	49
World	28	29

Source: PBL FAIR/IMAGE/TIMER model calculations and Enerdata (2010)

Figure 6.3
POLES mitigation costs compared to FAIR, 2030



Source: PBL FAIR/IMAGE/TIMER model calculations and Enerdata (2010) lower according to POLES than according to FAIR. Still, POLES data result in a more ambitious target for the EU than the proposed 40% target in this regime (namely 45%, which equals 41% below baseline levels). For most of the other regions, the reduction targets are quite similar. Only the reduction targets for India and Mexico differ by more than 3% with baseline levels – with lower reduction targets found by POLES. This indicates that the differences in cost curves between FAIR and POLES do not strongly influence regional reduction targets if the global emission level is taken as the starting point.

6.3 Mitigation costs

Figure 6.3 shows that, using the POLES cost curves, mitigation costs in the *convergence in per-capita emissions* regime are projected to be slightly higher in almost all regions. This is partly due to more stringent targets compared with the baseline (see Figure 6.2), and partly due to POLES cost curves assuming a lower potential, at a given carbon price, than the FAIR cost curves. With an equal carbon tax, mitigation costs are much higher when using POLES cost curves, as the carbon tax needed to achieve the EU 40% target is much higher. For the *equal relative costs* regime, the differences in mitigation costs are relatively small – again with POLES projecting higher costs.

Note

1 The same cost curves were used for reduction in CO_2 emissions from land use.

Annexes

Annex A: Methods and assumptions

A.1 Baseline assumptions

Baseline projections of CO_2 emissions from the energy, industry, household, waste and transport sectors were calculated by the TIMER energy model (Van Vuuren et al., 2006; Van Vuuren et al., 2011); non-CO_2 emissions from land use and agriculture were calculated by the IMAGE land-use model (Bouwman et al., 2006). These emission projections are based on the GDP projections calculated by the OECD ENV-Linkages model (Burniaux and Chateau, 2008) developed for the OECD Environmental Outlook to 2050 (OECD, 2012). The baseline emission projections include emission estimates from international aviation and shipping transport. Baseline projections of CO_2 emissions from forestry activities are based on two different models: an economic land-use model (GLOBIOM) and a detailed forestry model (G4M) (Kindermann et al., 2008; Kindermann et al., 2006). The economic land-use model GLOBIOM is located in the centre of the framework. The model uses recent baseline projections based on results from the POLES energy model for future bio-energy demand and related assumptions on population growth, economic development (GDP) and technical progress rates, such as macro-economic drivers. GLOBIOM represents the forestry, agriculture, bio-energy and livestock sectors in 28 world regions. The economic land-use model projects domestic production and consumption, net exports and timber and agricultural product prices.

For this study, the data were harmonised to match the emission levels of a historical dataset for the 1990–2005 period, compiled for the FAIR model. The dataset includes the greenhouse gases CO_2, CH_4, N_2O, HFCs, PFCs and SF_6. The data are based on national emission inventories, submitted to the UNFCCC (UNFCCC, 2008). Where not available (e.g. for all developing countries), other sources were used. For instance, CO_2 emissions from fuel combustion were taken from the International Energy Agency (IEA, 2006) and CH_4 and N_2O emissions in developing countries from the EDGAR database, version 4.0 (http://edgar.jrc.ec.europa.eu/).

In this baseline scenario, the global emission level (without implementation of pledges) would be around 57 Gt CO_2 eq by 2020 and 62 Gt CO_2 eq in 2030, from 45.5 Gt CO_2 eq in 2005. Harmonisation was carried out by applying harmonisation ratios at the country, sector and gas levels in 2005 to match the emission level of the baseline to that of the historical dataset. Harmonisation ratios converge from 2005 levels to unity in 2100. Therefore, harmonisation has implications for baseline emission levels by 2020 and 2030. In 2020, harmonised global emission levels are 2.4% higher than the original OECD baseline levels. In 2030, the difference is 1.9%.

The 1990 emission levels of developed countries were based on the 2008 submissions of countries to the UNFCCC. More recent submissions of countries to the UNFCCC slightly differ from the 2008 submissions. Other reasons why our 1990 emission levels differ from UNFCCC data are: i) we used Global Warming Potentials (GWPs) from the IPCC AR4 report (Forster et al., 2007) to aggregate emissions of different greenhouse gases to CO_2 equivalents, whereas the UNFCCC used GWPs from the IPCC SAR report (UNFCCC, 1995); and ii) we included CO_2 emissions from land use from the forestry model G4M, whereas the UNFCCC used national submissions for these CO_2 emissions.

The alternative dataset for POLES was based on the POLES reference scenario (i.e. in the absence of climate policy). The POLES baseline is broadly similar to the reference scenario of the IEA World Energy Outlook (IEA, 2009) and has been corrected for the economic crisis.

A.2 Calculating reduction targets and direct mitigation costs

The integrated modelling framework FAIR 2.3 (Den Elzen et al., 2011; Den Elzen and Höhne, 2008) was used for the quantitative analysis of emission reductions and mitigation costs at the level of 26 world regions. FAIR 2.3 uses marginal abatement cost (MAC) curves for calculating mitigation costs.

For energy- and industry-related CO_2 emissions, the MAC curves were determined using the TIMER energy model by imposing a carbon tax and recording the induced reduction in CO_2 emissions. TIMER is an energy system model that is part of the IMAGE integrated assessment framework. The TIMER energy model describes the long-term dynamics of the production and consumption of about 10 primary energy carriers for 5 end-use sectors in

26 world regions (Van Vuuren et al., 2006; 2007a). The model's behaviour is mainly determined by the substitution processes of various technologies based on long-term prices and fuel preferences. These two factors drive multinomial logit models that describe investments in new energy production and consumption capacity. The demand for new capacity is limited by the assumption that capital goods are only replaced at the end of their technical lifetime. The long-term prices that drive the model are determined by resource depletion and technology development. Resource depletion is important for both fossil fuels and renewables (for which depletion and costs depend on annual production rates). Technology development is determined using learning curves or through exogenous assumptions. Emissions from the energy system are calculated by multiplying energy consumption and production flows by emission factors. A carbon tax can be used to induce a dynamic response, such as the increased use of low- or zero-carbon technologies, energy efficiency improvements and end-of-pipe emission reduction technologies.

To explore the consequences of the uncertainty in cost estimates, we also used MAC curves information from the POLES model (Enerdata, 2010). POLES was selected to supplement the TIMER abatement costs since: (i) both models include a baseline accounting for the impact of the recent economic crisis; (ii) both models have information at the level of multiple sectors and world regions (both Annex I and non-Annex I), so can be incorporated in our integrated model; and (iii) both models show a wide range of outcomes across various models for Annex I as a group. The dynamics of the POLES model are based on a recursive simulation process of energy demand and supply with lagged adjustments to prices and a feedback loop through the international energy price. The model is developed in the framework of a hierarchical structure of interconnected modules at the international, regional and national levels. It contains technologically-detailed modules for energy-intensive sectors, including power generation, iron and steel, the chemical sector, aluminium production, cement making, non-ferrous minerals and modal transport sectors (including aviation and maritime transport). All energy prices are determined endogenously. Long-term oil prices depend primarily on the relative scarcity of oil reserves. The world is broken down into 47 regions, for which the model delivers 10 detailed energy balances.

For non-CO_2 greenhouse gas emissions, MAC curves from the EMF21 project (Weyant et al., 2006) were used. These curves were made consistent with the business-as-usual emission levels used here and made time dependent to account for technology change and the removal of implementation barriers (Lucas et al., 2007).

For CO_2 emissions from forestry activities, sector-specific information from the economic land-use model GLOBIOM was used by the forest model G4M to project greenhouse gas emissions and removals for detailed land management options. The forestry model was applied to estimate emissions, removals and MAC curves from forest management and afforestation/reforestation activities. MAC curves were derived by introducing a carbon price, which means that i) forest owners are paid for any carbon that is stored in forest living biomass above baseline level, and ii) they have to pay a tax if the amount of carbon in forest living biomass is below the baseline level. The following mitigation measures in forestry are considered in the G4M model:

- reductions in deforestation area;
- increases in afforestation area;
- changes in rotation lengths of existing managed forests in different locations;
- changes in the ratio between thinning and final fellings;
- changes in harvest intensity (amount of biomass extracted in thinning and final felling activities).

These activities are not adopted independently by forest owners. The model manages land dynamically and one activity affects the other. The model calculates the optimal combination of measures. The introduction of a CO_2 price gives an additional value to the forest through the carbon stored and accumulated in it. The increased value of forests under a regime that involves a CO_2 price alters the balance of land-use change through the net present value generated by land-use activities towards forestry. Parameterisation of the MAC curves was harmonised with assumptions made by the FAIR models to ensure consistency.

The following general assumptions were made for the abatement cost and carbon market calculations:

i. The cost calculations include the costs of emission reductions of all Kyoto greenhouse gases from all sources, including CO_2 emissions from land use and land-use change (deforestation).
ii. For the Kyoto period (2008–2012), all developed regions achieve their Kyoto target, except when this would lead to surplus emissions and except for Canada and the United States. Canada announced its withdrawal from the Kyoto Accord following the climate negotiations in Durban, while the United States did not ratify the Kyoto Protocol. We have therefore assumed baseline emission levels for these countries by 2010.
iii. No banking or carry-over of surplus emission units from the first commitment period and/or the period after 2012 is allowed.

iv. For the period 2012–2020, all developed countries implement their low pledges put forward by Parties in the Cancún Agreements (UNFCCC, 2010) (see Annex B).
v. To achieve the pledges made for 2020, developed countries may use credits from land-use activities that reduce CO_2 emissions. These credits amount to about 160 Mt CO_2, based on estimates of the minimum amount of credits and debits for the second commitment period (Grassi et al., 2012). It is assumed that Canada, the United States, Australia and the EU do not use land-use credits, as these countries have indicated that they will not use land-use credits to achieve their pledges. The targets by 2030 were calculated by assuming that countries can use their full potential to reduce CO_2 emissions from land use, therefore land-use credits are no longer relevant.

A.3 Calculating welfare effects

Welfare effects were calculated using the WorldScan model. WorldScan is a multi-region, multi-sector, recursive dynamic computable general equilibrium model with worldwide coverage. A detailed description of the model is given in Lejour et al. (2006). The model has been used for various kinds of analyses, in particular with respect to climate change policies. WorldScan includes emissions of non-CO_2 greenhouse gases and the possibility to invest in emission control by modelling MAC curves for emissions in each sector. These MAC curves mainly include 'end-of-pipe' abatement options, removing emissions largely without affecting the emission-producing activity itself.

WorldScan data for the base year were to a large extent taken from the GTAP-7 database (Narayanan and Walmsley, 2008) that provides integrated data on bilateral trade flows and input-output accounts for 57 sectors and 113 countries. The aggregation of regions and sectors can be flexibly adjusted in WorldScan. The version used here features 25 regions (largely similar to the regions in TIMER) and 13 sectors. The electricity sector is divided into five technologies: (i) fossil electricity with coal, oil and natural gas as imperfectly substitutable inputs, (ii) wind (onshore and offshore) and solar energy, (iii) biomass, (iv) nuclear energy, and (v) conventional hydropower (Boeters and Koornneef, 2011). The MAC curves for wind energy and biomass were calibrated on the data on the cost and potential of these technologies in TIMER. The carbon capture and storage option was included as an end-of-pipe option for the mitigation of CO_2 emissions from power plants, using region-specific data on the cost of carbon capture and storage and potential in TIMER.

In this study, WorldScan simulated deviations from the baseline by imposing restrictions on emissions given by the FAIR model. The baseline used here was the same as used for calculating the direct mitigation costs, but excluded CO_2 emissions from the forestry sector.

In WorldScan, environmental policies are simulated by the introduction of a carbon price (in this study, as a result of imposing a restriction on emissions). For emissions directly related to the use of a specific input, such as fossil fuels, the carbon price will lead to an increase in the user price of this input. Consequently, the demand for this input will decrease (either by using less energy or by substituting more carbon-emitting fuels for less carbon-emitting ones), leading to a reduction in emissions. As a result of these changes, the production costs increase. For emissions related to sectoral output levels, the carbon price will cause a rise in the output price of the associated product. The increase in the output price will lead to a decrease in demand for this product (as consumers substitute goods that become more expensive with other goods), which will reduce emissions. Moreover, if emission control options are available, these will be implemented up to the level at which the marginal cost of emission control equals the emission price.

To assess welfare effects, the concept of Hicksian equivalent variation (EV) was used to provide a cardinal welfare measure. The EV is defined as the amount of money by which the income of a household in the baseline situation would need to change to attain the utility level of an alternative situation in which prices have changed, for instance due to policy measures.

Annex B: Pledges and long-term targets

The 2020 emission levels resulting from a low pledge scenario were used as the starting point for the analysis. In this scenario, the EU reduces emissions by 20% relative to its 1990 emission level and all other regions implement their least ambitious pledge (if they only have one pledge, they implement that pledge). The emission levels by 2020 resulting from the low pledge scenario were based on Den Elzen et al. (2012), with the difference that this study, contrary to Den Elzen et al., included emissions from international shipping and aviation and CO_2 emissions from land use for developed countries. Table B.1 compares the baseline emissions and the emission levels resulting from the low pledges.

Table B.2 lists the long-term targets announced by individual countries (taken from the individual country assessments by http://climateactiontracker.org/, accessed 28 June 2012), used for comparison with the range of emission reductions resulting from the effort-sharing approaches.

Table B.1
Greenhouse gas emissions, including CO_2 emissions from land use and international shipping and aviation, as a result of the low pledge scenario (Mt CO_2 eq)

	1990	2005	2020, baseline	2020, low pledge
Western and Central Europe	6,042	5,601	5,685	4,824
USA	6,286	7,261	7,036	6,042
Canada	701	863	846	643
Oceania	671	848	903	673
Japan[1]	1,204	1,347	1,293	903
Korea	511	908	1,123	1,015
Russia	3,651	2,374	2,715	2,715
Turkey	227	343	526	526
China	4,101	8,176	14,933	14,131
India	1,434	2,224	3,987	3,987
Indonesia	768	1,061	1,164	1,164
Mexico	603	776	811	644
Brazil	1,953	2,473	2,614	2,160
Rest South America	1,467	1,734	1,902	1,716
Middle East	955	1,765	2,416	2,388
South Africa	398	509	637	521

Source: PBL FAIR/IMAGE/TIMER model calculations

[1] *For Japan, a 25% reduction relative to 1990 levels is assumed, although there are indications that Japan will set a new, less ambitious, target (Masaki, 2012).*

Table B.2
Announced long-term emission reduction targets

	Year	Reduction (%)	Relative to	Status
EU	2050	80–95	1990	Adopted
USA	2030	42	2005	Announcement
Canada	2050	60–70	2006	Announcement
Australia	2050	60	2005	Adopted
New Zealand	2050	50	1990	Announcement
Japan	2050	60–80	2005	Announcement
Russia	2050	50	1990	Announcement
Mexico	2050	50	2002	Adopted

Annex C: Detailed results emission allowances

Table C.1

Emission allowances by 2030 resulting from the effort-sharing approaches, including CO_2 emissions from land use and international shipping and aviation (Mt CO_2 eq)

	Baseline	Convergence in per-capita emissions	Equal carbon tax	Equal relative costs	Equal relative costs, 2° C
FAIR					
Western and Central Europe	5,565	3,632	3,636	3,656	3,198
USA	7,022	4,589	4,359	4,704	3,982
Canada	837	494	580	620	547
Oceania	917	523	617	661	605
Japan	1,275	662	769	794	665
Korea	1,087	729	810	852	776
Russia	2,525	1,848	1,974	2,160	2,035
Turkey	706	447	522	536	479
China	16,372	10,782	11,930	13,326	12,297
India	5,355	4,522	4,451	4,633	4,348
Indonesia	1,326	1,163	1,041	1,169	1,079
Mexico	878	550	570	612	540
Brazil	2,544	1,662	1,296	1,743	1,385
Rest South America	2,228	1,431	1,330	1,530	1,385
Middle East	3,026	2,048	2,425	2,631	2,469
South Africa	792	403	450	563	509
Rest of world	9,896	9,020	8,307	8,690	8,331
World	62,350	44,505	45,065	48,880	44,630
POLES					
Western and Central Europe	5,180	3,372	3,359	3,369	3,040
USA	7,648	4,405	4,074	4,538	4,184
Canada	927	465	542	636	594
Oceania	926	501	564	610	582
Japan	1,303	623	765	769	712
Korea	1,162	782	691	838	784
Russia	2,857	1,852	1,677	2,332	2,231
Turkey	558	403	306	349	319
China	17,374	10,662	10,216	13,660	13,004
India	5,797	4,675	3,826	5,087	4,914
Indonesia	1,093	1,037	740	908	852
Mexico	776	512	519	530	503
Brazil	2,211	1,514	1,057	1,231	1,137
Rest South America	1,895	1,354	1,067	1,185	1,136
Middle East	2,745	1,929	1,995	2,311	2,222
South Africa	660	362	259	396	365
Rest of world	9,616	8,890	7,399	8,294	8,077
World	62,728	43,339	39,056	47,042	44,656

Annex D: Detailed results on sectoral effects

Table D.1

Sectoral effects on production, share in world production and employment in EU (deviation from baseline)

	Convergence in per-capita emissions (%)	EU only (%)	EU only + border measures (%)	Fragmented action (%)	Fragmented action + border measures (%)
Production					
Energy-intensive industry	-1.8	-3.8	-2.8	-3.2	-2.9
Other industry	-0.6	-1.0	-1.3	-0.8	-0.9
Electricity	-10.0	-11.9	-11.8	-11.2	-11.2
Energy sector	-12.8	-12.0	-12.0	-12.3	-12.3
Agriculture	-4.9	-4.8	-5.0	-4.8	-4.9
Transport	-2.0	-2.8	-2.9	-2.7	-2.7
Services	0.2	0.2	0.2	0.2	0.2
Share in world production					
Energy-intensive industry	0.3	-3.6	-2.5	-2.3	-2.0
Other industry	0.8	-0.8	-1.2	-0.2	-0.3
Electricity	-2.4	-10.0	-9.9	-7.1	-7.0
Energy sector	-1.2	-10.8	-10.7	-7.6	-7.6
Agriculture	-2.1	-4.5	-4.7	-3.8	-3.9
Transport	-0.4	-2.3	-2.4	-1.7	-1.7
Services	0.2	0.2	0.2	0.2	0.2
Employment					
Energy-intensive industry	-0.5	-2.1	-1.1	-1.6	-1.3
Other industry	-0.5	-0.6	-1.0	-0.5	-0.6
Electricity	-41.9	-43.2	-43.1	-42.7	-42.7
Energy sector	-38.4	-30.8	-30.9	-33.7	-33.8
Agriculture	-3.5	-3.2	-3.4	-3.3	-3.3
Transport	-0.7	-0.8	-0.9	-0.8	-0.8
Services	0.2	0.4	0.3	0.3	0.3

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