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GLOBAL AND REGIONAL GREENHOUSE GAS EMISSIONS NEUTRALITY

Implications of 1.5 °C and 2 °C scenarios for reaching net zero greenhouse gas emissions

Note

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Global and Regional Greenhouse Gas Emissions Neutrality

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Main findings

The issue of greenhouse gas emissions neutrality as indicated in the Paris Agreement is increasingly gaining interest among policymakers. However, key questions need to be addressed before the concept could be used. The Paris Agreement is aimed to keeping global warming to well below 2 °C and to pursue efforts to limit it further, to 1.5 °C. These targets, in themselves, do not provide any guidance for policymakers and investors about how to achieve them. As part of a stocktaking process, policymakers are looking into various reduction targets and policy measures that could contribute to the climate targets. The Paris Agreement also states the aim of global greenhouse gas (GHG[1]) emissions peaking as soon as possible, and of achieving a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century. The second aim is often referred to as the concept of greenhouse gas emissions neutrality. This publication discusses some of the relevant questions related to this concept. It includes an overview of the literature and of Integrated Assessment Model (IAM) runs and identifies knowledge gaps. It addresses the following three overarching policy questions:

1. *What are the main principles of greenhouse gas emissions neutrality—and what key open questions are related to this concept?*
   - Greenhouse gas emissions neutrality is here defined as reducing global emissions of all greenhouse gases to net zero, and is distinguished from ‘climate neutrality’.
2. *What could be the global and regional implications of the emission pathways towards achieving greenhouse gas emissions neutrality?*
   - Global greenhouse gas emissions are projected to reach net zero between 2080 and 2100 and for CO_2, this will be between 2055 and 2070, under scenarios that limit global warming to 2 °C with a 66% probability and that do not have technology limitations.
   - In most regions, greenhouse gas emissions are projected to peak by 2020, with the earliest achievement of net zero greenhouse gas emissions occurring in 2060.
   - Corresponding emission reductions by 2050 are 59% for China, 74% for the EU, 16% for India and 85% for the USA, relative to 2010. For the EU, this means reductions of 47% by 2030 and 80% by 2050, relative to 1990 (including LULUCF CO_2), noting that these results are for cost-optimal scenarios that do not account for fairness considerations.
   - Achieving the aspirational 1.5 °C target would further increase the reduction targets for all countries.
   - Effort-sharing studies that have calculated emission allowances by applying different equity principles to global emissions pathways consistent with achieving 2 °C or 1.5 °C, show even larger reduction targets for OECD countries, including those in the EU.
   - Greenhouse gas emissions neutrality does not imply full decarbonisation, as remaining emissions can be compensated for by negative emissions from LULUCF sinks and through biomass used in energy production coupled with carbon capture and storage.
   - Therefore, regions with a large potential for negative emissions show earlier phase-out years, although the allocation of negative emissions to either the biomass-

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[1] GWP-aggregated emissions of all Kyoto greenhouse gases. In the remainder of the report, greenhouse gas emissions include CO_2 emissions from land use, land-use change and forestry (LULUCF), unless indicated otherwise.

producing region or the region applying it with CCS does influence regional phase-out projections.

3. *What are the land-use implications of achieving greenhouse gas emissions neutrality?*
    - The global area of land dedicated to energy crops varies across models, and is projected to be between 180 million ha and 1084 million ha by 2100, while the projected increase in global forest area, as a function of afforestation/reforestation and deforestation for bioenergy crops, ranges from 150 million ha to 820 million ha by 2100, relative to 2010.

Executive summary

The issue of greenhouse gas emissions neutrality as indicated in the Paris Agreement is increasingly gaining interest among policymakers. However, key questions need to be addressed before the concept could be used. The Paris Agreement is aimed to keeping global warming to well below 2 °C and to pursue efforts to limit it further, to 1.5 °C. These targets, in themselves, do not provide any guidance for policymakers and investors about how to achieve them. As part of a stocktaking process, policy makers are looking into various reduction targets and policy measures that could contribute to the climate targets. The Paris Agreement also states the aim of global greenhouse gas (GHG[2]) emissions peaking as soon as possible, and of achieving a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century. The second aim is often referred to as the concept of greenhouse gas emissions neutrality. This publication discusses some of the relevant questions related to this concept. It includes an overview of the literature and IAM model runs and identifies knowledge gaps. It addresses the following three overarching policy questions:

1. What are the main principles of greenhouse gas emissions neutrality—and what key open questions are related to this concept?
2. What could be the global and regional implications of the emission pathways towards achieving greenhouse gas emissions neutrality?
3. What are the land-use implications of achieving greenhouse gas emissions neutrality?

What are the main principles of greenhouse gas emissions neutrality—and what key open questions are related to this concept?

There are a set of concepts related to greenhouse gas emissions neutrality. The concept of greenhouse gas emissions neutrality refers to the moment that the sum of all greenhouse gases (Kyoto gases) reaches zero. This is sometimes also referred to as climate neutrality. It should be noted that greenhouse gas emissions neutrality is defined by a sum of different emission categories, including energy-system CO_2 emissions, land-use related CO_2 emissions and non-CO_2 emissions. Some of the emissions are difficult to reduce. They can be compensated, however, by so-called negative emissions, i.e. CO_2 removal from the atmosphere. This can be done in different ways, including through the combination of bio-energy and CCS (BECCS), afforestation/reforestation, enhanced weathering and additional storage of carbon in soils. The combination of these different sources and sinks can lead to "greenhouse gas emissions neutrality" (see Figure S.1). On the basis of the IPCC Fifth Assessment Report and Levin et al. (2015a), some related concepts can be defined:

- *Carbon neutrality*: Reduce global annual anthropogenic CO_2 emissions to net zero (see *net-zero carbon emissions* below); achieved between 2055 and 2070

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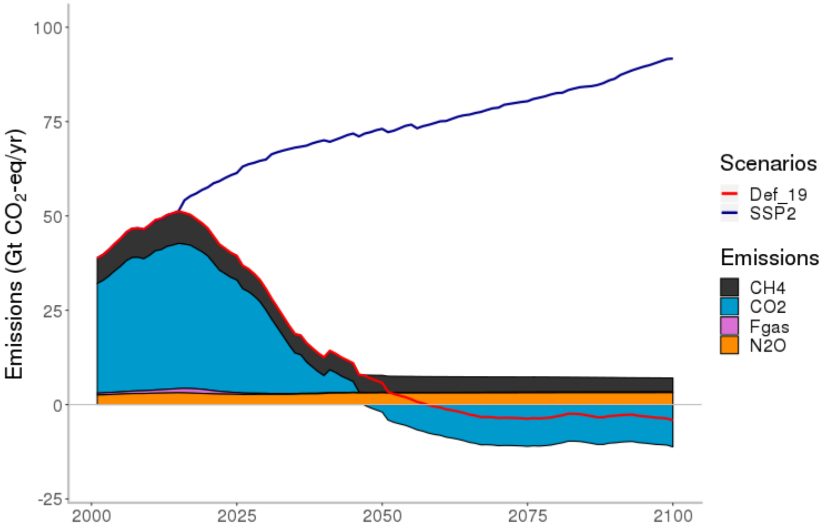
[2] GWP-aggregated emissions of all Kyoto greenhouse gases. In the remainder of the report, greenhouse gas emissions include CO_2 emissions from land use, land-use change and forestry (LULUCF), unless indicated otherwise.

- *Global carbon budget*: Remaining amount of cumulative CO_2 emissions to meet a climate target.
- *Net-zero carbon emissions*: Situation in which anthropogenic removal of CO_2 exceeds anthropogenic CO_2 emissions.
- *Net-zero greenhouse gas emissions:* Reduce emissions of all greenhouse gases to net zero between 2080 and 2100 (see also *climate neutrality*).
- *Peaking emissions*: Year of peak in global greenhouse gas emissions
- *Percentage of emissions reduction* by a certain date

Figure S.1. Pathways of global greenhouse gas emissions ($GtCO_2eq$/year) in 1.5 °C scenarios of the IMAGE integrated assessment model.



Source: This study, based on Van Vuuren et al. (2018)

There are different ways to define greenhouse gas emissions neutrality. As the concept of greenhouse gas emissions neutrality is defined as the sum of greenhouse gas emissions being zero, it directly depends on the use of metrics that equate the contribution of different greenhouse gases. The use of 20, 100 or 200-year global warming potentials (GWPs) or other equivalence metrics directly defines the moment in time "greenhouse gas emissions neutrality" is reached. This is also true for the way land-use related emissions are accounted for.

There is large uncertainty in land-use related CO_2 emissions, while also different definitions are used. Land-use related CO_2 emissions are very uncertain and researchers use different methods to estimate the emissions. It should also be noted that there are different ways to distinguish between natural and anthropogenic land-use related CO_2 emissions. In models, usually land-use related emissions are defined on the basis of land-use change. In contrast, in the reporting of most countries under UNFCCC, all changes in CO_2 stocks in managed forests are counted as anthropogenic. This thus includes the removal of additional CO_2 from the atmosphere by existing forests, which is accounted for as a natural CO_2 flow in most models. These definitions have a relatively small impact on total CO_2 emissions right now, but can strongly influence the overall emissions once other sources are reduced to near-zero (and thus the year greenhouse gas emissions neutrality is reached).

Further discussion on how to account for negative emissions is needed. A key source of possible negative emissions is BECCS. In BECCS application, the CO_2 removal physically takes place during biomass production ('at the field'). In accordance with the concept of accounting for ‘normal’ CO_2 emissions at the place of combustion, most models also assign negative emissions to the regions where combustion takes place. Clearly, how to properly assign negative emissions still needs to be discussed further. The year of greenhouse gas emissions neutrality of different regions strongly depends on these accounting tools.

While the concept of greenhouse gas emissions neutrality provides an attractive formulation of long-term ambition of different countries, further discussion is needed on how to best define this concept. In the previous conclusions, we discussed several issues that strongly impact results. Further discussion on how to best deal with these issues is needed. In the remainder of this summary, we illustrate possible outcomes, also in light of these uncertainties.

What could be the global and regional implications of the emission pathways towards achieving greenhouse gas emissions neutrality?

When would global greenhouse gas emissions need to reach net zero, under 2 °C scenarios?

The form of the emission profile strongly depends on societal choices regarding overshoot and timing and the availability of different technologies. The AR5 report indicates, using the full set of scenarios available at the time, that global greenhouse gas emissions would need to reach net zero between 2080 and 2100, in order to stay within the 2 °C limit with a 66% probability. This conclusion, however, depends on the assumed negative emissions and the possible overshoot. In any case, CO_2 emissions would need to reach zero earlier. In optimal scenarios this happens between 2055 and 2070, but this depends on the assumed starting date of cost-optimal reductions that are to achieve this goal.

What does greenhouse gas emissions neutrality mean, with respect to CO_2 and non-CO_2 emissions?

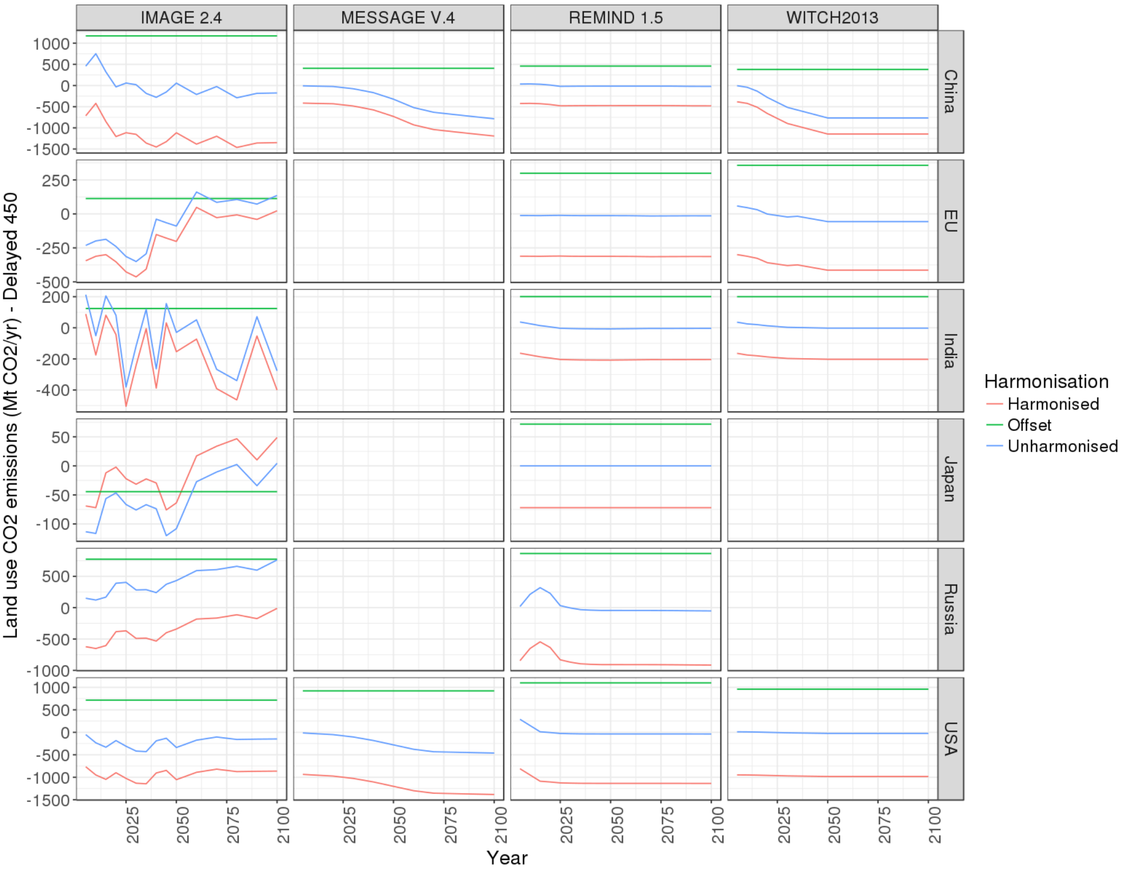
Greenhouse gas emissions neutrality does not imply full decarbonisation, as the remaining emissions of CO_2 in the transport, industry and building sectors, and of non-CO_2 greenhouse gases, mostly in agriculture, can be compensated for by negative emissions from LULUCF sinks (mainly forests) and through the use of biomass in energy production coupled with Carbon Capture and Storage (BECCS).

When would national and regional greenhouse gas emissions need to reach net zero, under 2 °C scenarios?

We have discussed earlier that regional projections of phase-out years depend strongly on how negative emissions achieved through BECCS are allocated: to the region producing the biomass, or to the region applying it with CCS? Using the latter definition (consistent with the IAM models), the earliest achievement of net zero greenhouse gas emissions occurs in 2060, and of net zero CO_2 emissions in 2050, for some regions, while most regions are projected to reach net zero later, based on the analysis of model scenarios of the LIMITS and AMPERE projects (Kriegler et al., 2014c; Riahi et al., 2015). For regions with larger shares of non-CO_2 emissions and/or less potential to create negative emissions, this moment occurs later in time.

Differences in land-use accounting methods strongly affect the year greenhouse gas emissions neutrality is reached. As indicated earlier, uncertainty in land-use related CO_2 emissions is large, while this is confounded by the different definitions that are used. The EU, China and the United States report carbon sinks for managed forests, which are projected to remain more or less the same in the future. Models, however, consider this to be a natural CO_2 sink caused by carbon fertilisation. This discrepancy can be removed by harmonising definitions. It is possible to get some idea of the impact of this definition of ‘harmonisation’ by, in this case, adding the absolute emissions difference in 2010 between the inventory data and the model data to the model projections (see Figure S.2). This leads to shifting the absolute values of the emission projections up or down, without changing the trend.

Figure S.2. Effect of harmonisation on the emission pathways for land use CO_2 emissions, in delayed mitigation 450 ppm CO_2eq scenarios, per model and region. Source: This study.



Unharmonised model land use CO_2 emissions (blue), constant offset value (model data minus inventory data, green), and harmonised model land use CO_2 emissions (red, i.e. blue minus green). These harmonised land use CO_2 emissions are then added to the unharmonised greenhouse gas emissions excluding land use CO_2, to generate total greenhouse gas emission pathways including land use CO_2.

The shift in LULUCF CO_2 emissions explored here leads, on average, to projected phase-out dates for greenhouse gases and CO_2 that are approximately 5 to 15 years earlier, as 2010 emission levels as calculated by models are generally higher than those from officially reported emissions data. Harmonising the model projections towards the countries’ land use emissions estimates results in net zero or negative emissions being achieved sooner, as illustrated in Table S.1 for some selected countries. The shift especially affects projected phase-out years for countries where LULUCF emissions play an important role (e.g. China, the EU and the United States, with reported carbon sinks). At the same time, also uncertainty still plays a large role. The linear shift also leads to a convergence of the phase-out years for OECD countries, including the EU as a group, to around 2050–2070, which is earlier than for most of the non-OECD countries. Low-income countries, such as India, have projected phase-out years at the end of the century.

Table S.1. Projected regional phase-out years (median estimates) for greenhouse gas emissions (columns 1 and 2) or CO_2 emissions only (columns 3 and 4), under delayed mitigation scenarios[3] (cost-optimal allocation of reductions implemented after 2020), without harmonisation (columns 1 and 3) and with harmonisation to CO_2 emissions from LULUCF (columns 2 and 4).

	Phase-out year for all greenhouse gas emissions		**Phase-out year for all CO_2 emissions**		**Phase-out year relative to World**
Country/ region [no. of models]	No harmonisation	Harmonisation of CO_2 emissions from LULUCF	No Harmonisation	Harmonisation of CO_2 emissions from LULUCF	No harmonisation
China [4]	2100	2090	2075	2070	Same
EU [3]	No phase-out	2080	2080	2060	Later
India [3]	No phase-out	No phase-out	2090	2080	Later
Japan [2]	2065	2065	2055	2060	Earlier
Russia [2]	2085	2075	2080	2055	Earlier
United States [4]	2065	2060	2060	2045	Earlier
World [4]	2100	-	2065	-	-

Only regions that are covered by at least two models are shown here. See Appendix IV for indicative results on other regions. Years should be interpreted with care, as models generally report their emission projections in 10-year time steps.

What are the regional emission reductions by 2030 and 2050 resulting from the greenhouse gas emission pathways that meet 2 °C with a likely chance?
Scenarios that start cost-optimal mitigation in 2020 and meet 2 °C with a likely chance show median emission reductions of 12% by 2030 and 59% by 2050 for China, 36% by 2030 and 74% by 2050 for the EU, 32% by 2030 and 85% by 2050 for the USA, and an increase of 45% by 2030 followed by a reduction of 16% by 2050 for India, relative to 2010 and including LULUCF CO_2. For the EU, this means reductions of 47% by 2030 and 80% by 2050, relative to 1990 (including LULUCF CO_2). Achieving the aspirational 1.5 °C target would further increase the reduction targets for all countries. Various studies have calculated emission allowances by applying different equity principles to global emissions pathways consistent with achieving 2 °C or 1.5 °C. These studies show larger reductions targets for OECD countries, including those in the EU.

What does greenhouse gas emissions neutrality mean, with respect to national CO_2 and non-CO_2 emissions?
Countries with early phase-out generally have a relatively large potential for negative emissions and relatively low emission levels of both CO_2 (from the transport, industry and building sectors) and non-CO_2 greenhouse gases. Contrasting the OECD90+EU region to the Latin America region shows relatively larger remaining F-gas and transport CO_2 emissions in OECD countries, while Latin American countries show a relatively larger contribution from land use to negative emissions, albeit relatively large remaining CH_4 emissions due to agricultural production. High potential for negative emissions from reforestation and

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[3] This subset of mitigation scenarios (called delayed mitigation scenarios in this report) consists of scenarios that have a likely chance of staying within the 2 °C limit, have modest emission reductions up to 2020, assume country pledges are fully implemented by 2020, and assume cost-optimal mitigation afterwards in order to achieve the 2 °C target.

increased managed forest area is related to low land costs and high forest growth rates in Latin America.

When would global greenhouse gas emissions need to reach net zero, under 1.5 °C scenarios?
To limit global warming to 1.5 °C, emissions need to peak earlier and be reduced faster and deeper compared to 2 °C pathways. Global greenhouse gas emissions would need to reach net zero between 2050 and 2070, for a medium to likely chance of achieving the 1.5 °C target.

What would be the land-use implications of achieving greenhouse gas emissions neutrality?

What would be the general land-use implications related to the 2 °C scenarios?
According to integrated assessment models (here, IMAGE, MESSAGE-GLOBIOM, AIM/CGE, GCAM4, REMIND-MAGPIE), the dynamics of agricultural production are expected to be affected by land-demanding mitigation options, such as afforestation, avoided deforestation, improved agricultural management and bioenergy crop production. Dedicated energy crops are expected to play a critical role in 2 ºC scenarios. The global area of land dedicated to energy crops, however, varies significantly across IAMs. The 2 °C scenarios project that, by 2100, between 180 million ha (IMAGE) and 1084 million ha (GCAM) are expected to be allocated to energy crops—compared to currently less than one million ha.

How do these strategies impact the forest area?
The forest area is a function of possible reforestation/afforestation actions, on the one hand, and possible deforestation resulting from bio-energy production. On average, most models see a reduction of deforestation rates. The net loss of forest land would need to be halted by 2030 and change to an increase in forest area thereafter. The projected increase in forest area varies significantly between IAMs. The increase in global forest area ranges from a moderate 150 million ha (REMIND-MAGPIE), to a significant 820 million ha (AIM/CGE) for the year 2100, compared to the situation of 2010.

What could be consequences of these land-use related strategies?
As shown in other publications, additional land-use for mitigation has impacts on food prices and biodiversity. However, food availability and agricultural commodity prices may differ significantly, depending on how mitigation policies are implemented and which sectors are specifically targeted by a policy measure. Similar uncertainty also holds for biodiversity. Some models project that under the baseline scenario, developments may lead to the conversion of a significant number of high biodiversity areas (220 million ha, globally, over the period from 2010 to 2050). Staying at or below the 2 °C temperature increase may have a relatively limited negative impact on the conversion of high biodiversity areas, and may only lead to an additional 20 million ha of high biodiversity areas being converted, globally, by 2050.

1. Background and objectives

In December 2015, at the climate summit in Paris, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement (UNFCCC, 2015). Parties agreed to keep the increase in global average temperature to well below 2 °C above pre-industrial levels, and to pursue efforts to limit temperature rise further to 1.5 °C (Article 2 of the Paris Agreement). In order to achieve these long-term temperature goals, Parties further agreed to '*reach global peaking of greenhouse gas emissions as soon as possible […] and […] to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century.' (UNFCCC, 2015)*

This *balance between greenhouse gas emission sources and sinks*, in essence, means reaching greenhouse gas (GHG[4]) emissions neutrality. In the literature, the term 'climate neutrality' is also used instead of greenhouse gas emissions neutrality (with a more or less similar meaning), but the latter is more specific than the former. The advantage is that it specifically indicates that neutrality refers to the sum of greenhouse gas emissions (thus excluding climate forcers such as aerosols and changes in albedo, also through geoengineering options such as solar radiation management and cloud seeding). That is why we opted for *greenhouse gas emissions neutrality*.

The issue of greenhouse gas neutrality as indicated in the Paris Agreement is increasingly gaining interest among policymakers. However, key questions need to be addressed before the concept could be used. This publication discusses some of the relevant questions related to this concept. It includes an overview of the literature and of Integrated Assessment Model (IAM) runs and identifies knowledge gaps. The study focuses on the following three overarching policy questions:

1. What are the main principles of greenhouse gas emissions neutrality—and what key open questions are related to this concept?
2. What could be the global and regional implications of the emission pathways towards achieving greenhouse gas emissions neutrality?
3. What are the land-use implications of achieving greenhouse gas emissions neutrality?

Chapter 2 defines some key concepts, Chapter 3 deals with greenhouse gas emissions pathways implications of greenhouse gas emissions neutrality, Chapter 4 gives an overview of negative emissions options, and Chapter 5 zooms in on some of those options and their implications for the land-use sector.

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[4] GWP-aggregated emissions of all Kyoto greenhouse gases. In the remainder of the report, emissions include CO_2 from LULUCF, unless indicated otherwise.

2. Main principles of greenhouse gas emissions neutrality and open questions

What is meant by 'greenhouse gas emissions neutrality' and 'carbon neutrality'?

The following definitions are used in this report (Höhne et al., 2015):

- *''Climate neutrality' on the global scale is equivalent to the net phase out of all greenhouse gas emissions.'*
- *''Carbon neutrality' is a very similar concept, but for carbon dioxide (CO_2) emissions only'.*

In the remainder of this report, we will refer to greenhouse gas emissions neutrality rather than climate neutrality for clarity, because climate neutrality is not clearly defined, possibly leading to different interpretations. For example, climate neutrality could be interpreted to relate to radiative forcing, i.e. allowing for geoengineering approaches other than those that affect greenhouse gases, such as solar radiation management. As our focus is on greenhouse gas emissions, 'greenhouse gas emissions neutrality' seemed a more appropriate term, referring to the moment that the sum of all greenhouse gas (Kyoto gas) emissions reaches zero.

The World Resources Institute (WRI) (Levin et al., 2015a) offers a glossary of terms related to the long-term goal of the Paris Agreement. It defines carbon neutrality as *'annual zero net anthropogenic (human-induced or influenced) CO_2 emissions by a certain date'.* In Levin et al. (2015b), the concept of greenhouse gas emissions neutrality is explained in detail, as this concept was introduced in the draft Paris Agreement at that time: *'Greenhouse gas (GHG) emissions neutrality should be interpreted to mean net zero anthropogenic GHG emissions from all sectors. It is achieved first and foremost by reducing total GHG emissions to as close to zero as possible. Any remaining GHGs would be balanced with an equivalent amount of removals (such as enhanced sequestration in the land sector) or negative emissions (possibly using future technologies like bioenergy combined with carbon capture and sequestration'*. Summarising, greenhouse gas emissions neutrality is the same concept as carbon neutrality, but rather than only focusing on CO_2 emissions, it includes net zero anthropogenic greenhouse gas emissions.

It should be noted that greenhouse gas emissions neutrality is defined by a sum of different emission categories, including energy-system CO_2 emissions, land-use related CO_2 emissions and non-CO_2 emissions. Some of the emissions are difficult to reduce. They can be compensated, however, by so-called *negative emissions*, i.e. CO_2 removal from the atmosphere. This can be done in different ways, including through the combination of bio-energy and CCS (BECCS), afforestation/reforestation, enhanced weathering and additional storage of carbon in soils. The combination of these different sources and sinks can lead to "greenhouse gas emissions neutrality", i.e., *net zero* emissions.

Rogelj et al. (2015b) provide a scientific clarification of zero-emission concepts (see their Table 1). They define *carbon neutrality* as total annual CO_2 emissions from all anthropogenic sources being net zero, on a global level. In their definition, carbon neutrality is a synonym for the scientific term 'net zero carbon emissions'. Similarly, *climate neutrality* corresponds to net zero greenhouse gas emissions.

Both Levin et al. (2015b) and Butler et al. (2015) note that greenhouse gas emissions and carbon neutrality can also be applied on a smaller scale, relating to *'activities of an individual, an organisation, a city or a country'*. On that level, emission credits from offset mechanisms could be used to achieve neutrality.

Both greenhouse gas emissions neutrality and carbon neutrality link to the scientific understanding that global greenhouse gas emissions need to be brought to net zero to stabilise global temperatures (Evans and Pidcock, 2015). Neither of the terms ended up in the Paris Agreement, but they were considered during the negotiations (Evans and Pidcock, 2015). The final wording of the Paris Agreement (UNFCCC, 2015) in relation to the long-term goal (Evans, 2015) is (emphasis added):

> *'In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognising that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to* ***achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century****, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty'.*

The Paris Agreement framing of its long-term goal is most similar to greenhouse gas emissions neutrality.

What are key open questions related to the concept of greenhouse gas emissions neutrality?

There are different ways to define greenhouse gas emissions neutrality. As the concept of greenhouse gas emissions neutrality is defined as the sum of greenhouse gas emissions being zero, it directly depends on the use of metrics that equate the contribution of different greenhouse gases. The use of 20, 100 or 200-year global warming potentials (GWPs) or other equivalence metrics directly defines the moment in time "greenhouse gas emissions neutrality" is reached (see section 3.1.1). This is also true for the way land-use related emissions are accounted for.

There is large uncertainty in land-use related CO_2 emissions, while also different definitions are used (see section 3.3 and Appendix IV). Land-use related CO_2 emissions are very uncertain and researchers use different methods to estimate the emissions. It should also be noted that there are different ways to distinguish between natural and anthropogenic land-use related CO_2 emissions. In models, usually land-use related emissions are defined on the basis of land-use change. In contrast, in the reporting of most countries under UNFCCC, all changes in CO_2 stocks in managed forests are counted as anthropogenic. This thus includes the removal of additional CO_2 from the atmosphere by existing forests, which is accounted for as a natural CO_2 flow in most models. These definitions have a relatively small impact on total CO_2 emissions right now, but can strongly influence the overall emissions once other sources are reduced to near-zero (and thus the year greenhouse gas emissions neutrality is reached).

Further discussion on how to account for negative emissions is needed. A key source of possible negative emissions is BECCS. In BECCS application, the CO_2 removal physically takes place during biomass production (‘at the field’). In accordance with the concept of accounting for ‘normal’ CO_2 emissions at the place of combustion, most models also assign negative emissions to the regions where combustion takes place. Clearly, how to properly assign negative emissions still needs to be discussed further (see section 3.3). The year of greenhouse gas emissions neutrality of different regions strongly depends on these accounting tools.

While the concept of greenhouse gas emissions neutrality provides an attractive formulation of long-term ambition of different countries, further discussion is needed on how to best define this concept. Above, we discussed several issues that strongly impact results. Further discussion on how to best deal with these issues is needed. In the remainder of this publication, we illustrate possible outcomes, also in light of these uncertainties.

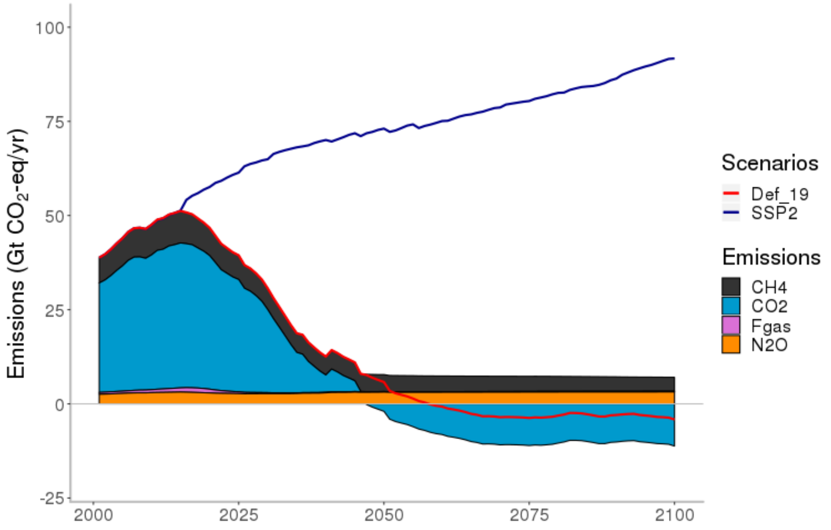
3. Global and regional implications of emission pathways towards greenhouse gas emissions neutrality

3.1 When would global greenhouse gas emissions need to reach net zero, under 2 °C scenarios?

The form of the emission profile strongly depends on societal choices regarding overshoot and timing and the availability of different technologies. The AR5 report indicates, using the full set of scenarios available at the time, that global greenhouse gas emissions would need to reach net zero between 2080 and 2100, in order to stay within the 2 °C limit with a 66% probability. This conclusion, however, depends on the assumed negative emissions and the possible overshoot. In any case, CO_2 emissions would need to reach zero earlier. In optimal scenarios this happens between 2055 and 2070, but this depends on the assumed starting date of cost-optimal reductions that are to achieve this goal.

In addition to the temperature target (e.g. 1.5–2 °C), the preferred *likelihood* of reaching the target and the assumed starting date of cost-optimal emission reductions (3.1.1), and the role of *negative emissions* (3.1.2) also matter. Figure 1 shows typical pathways in line with 2 °C, reaching greenhouse gas emissions neutrality by the end of the century.

Figure 1. Pathways of global greenhouse gas emissions (GtCO$_2$eq/year) in 1.5 °C scenarios of the IMAGE integrated assessment model.



Source: This study, based on Van Vuuren et al. (2018)

3.1.1 Literature review: The impact of the likelihood and the assumed start date of cost-optimal emission reductions on reaching the temperature target

Höhne et al. (2015) summarised the projected timing of net zero greenhouse gas emissions for reaching 2 °C with various likelihoods (Table 1). Their analysis was based on scenarios that assume emission reductions start immediately (2010), and distribute reductions cost-optimally over time. Main findings are:

- For a likely chance (more than 66%) of achieving the 2 °C target (IPCC category 430–480 ppm CO$_2$ equivalents), global emissions of all greenhouse gases need to be net zero by 2100. The global CO$_2$ emissions will reach net zero by 2070 (30 years earlier). Most scenarios assume that it is more difficult to reduce emissions of N$_2$O and CH$_4$ from agriculture to zero. Therefore, negative CO$_2$ emissions are needed to reach net zero greenhouse gas emissions.
- For a medium chance (33%–66%) of achieving the 2 °C target, the timing of net zero emissions is approximately five years later. The emission reductions early on are lower.

Table 1. Summary of timing of reaching net zero greenhouse gas and CO$_2$ emissions, and emission reductions by 2030 and 2050, for cost-optimal pathways (starting in 2010).

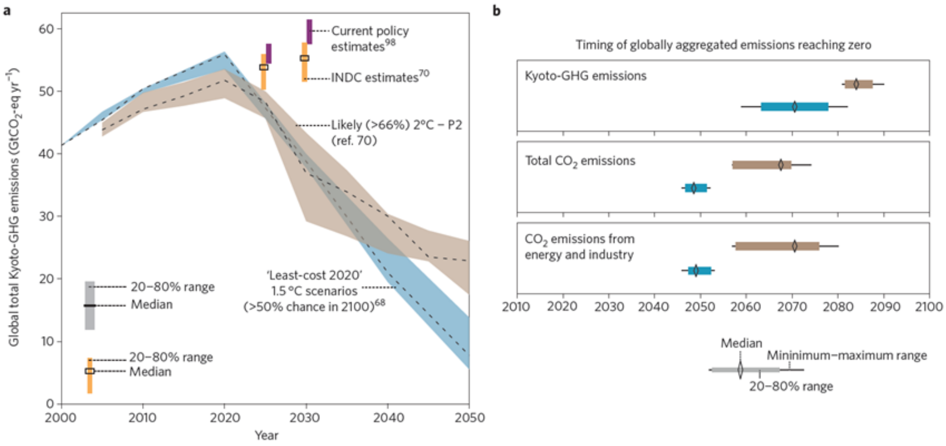
	Net zero year		**Change in GHG emissions relative to 2010[1] levels**		
Chance of staying below 2 °C by 2100	**All GHG**	**CO$_2$**	**2030**	**2050**	**2100**
Likely chance (>66%)	2100	2070	[-40%;5%]	[-45%; -65%]	[-118%;-78%]
Medium chance (33%–66%)	2100	2075	[-30%;20%]	[-40%;-60%]	[-73%;-21%]

[1] For comparison to 1990 levels: GHG emissions have increased from 38 GtCO$_2$eq in 1990 to 51 GtCO$_2$eq in 2010 (EDGAR database, JRC/PBL, 2014).

Source: Höhne et al. (2015)

Rogelj et al. (2015b) and Schleussner et al. (2016) did a similar analysis with these scenarios, but focused on the mitigation scenarios that account for the implementation of the 2020 pledges. They found that the pledges for 2020 would imply that global total CO_2 emissions need to reach net zero between 2060 and 2070 for a likely (>66%) chance of staying below 2 °C, i.e. somewhat earlier than under scenarios starting cost-optimal mitigation in 2010, with net negative CO_2 emissions thereafter (Figure 2). Because of residual non-CO_2 emissions, net zero is always reached later for total greenhouse gas emissions than for CO_2. The emissions can be phased out later for lower likelihoods of achieving the target. Only a limited number of model scenarios were available for a target of 1.5 °C with a >50% chance in Rogelj et al. (2015b) and Schleussner et al. (2016), and these assume relatively high global emissions by 2020, compared to the larger set of model scenarios that have pathways towards 2 °C with a >66% chance (compare blue area with brown area in Figure 2).

Figure 2. Characteristics of 1.5 °C and 2 °C scenarios



The colours in panel b correspond to the colours in panel a. Source: Schleussner et al. (2016) (see also Rogelj et al. (2015b) for a similar figure).

UNEP (2014) has analysed the impact of starting cost-optimal emission reductions in 2020 instead of 2010, based on a scenario assessment. Their analysis showed that the higher the net global emissions in the near term, the higher the required level of negative emissions in the second half of the century, and the earlier the timing of reaching net zero emissions. For 2 °C scenarios starting cost-optimal mitigation in 2020, global greenhouse gas emissions are projected to reach net zero by 2085 (2080–2100), and CO_2 emissions by 2070 (2060–2075) (Table 2). This is about 20 years (all greenhouse gases) and five years (CO_2) earlier, compared to under the least-cost 2010 scenarios. However, taking 2010–2012 as the beginning of the cost-optimal mitigation period is not realistic, given historical trends in greenhouse gas emissions and the current status of international climate policy. UNEP (2016), therefore, does not extensively discuss these scenarios, but instead focuses on the delayed mitigation pathways. Two main reasons for this choice of focus were: 1) actual emissions since 2010 have been higher than under 2 °C scenarios with a least-cost pathway beginning in 2010 (rather than 2020); 2) least-cost delayed (2020) mitigation scenarios seem to be more in line with current policies projections of 2020 emissions.

Studies comparing cost-optimal and delayed mitigation pathways generally conclude that delay implies more rapid and deeper decarbonisation after 2030. Such delayed mitigation pathways may still phase-out global greenhouse gas emissions by the end of the century (Kriegler et al., 2014b; Kriegler et al., 2014c), but the compensation for the delay is mainly concentrated during the 2030–2050 period (Kriegler et al., 2014b). This period shows historically unprecedented emission reduction rates, rapid scale-up of low-carbon energy

technologies and early retirement of carbon-intensive infrastructure (Kriegler et al., 2014b). In addition, delaying cost-optimal mitigation until 2030 implies an increased reliance on the availability of specific technologies such as CCS and (large-scale use of) bioenergy to achieve the agreed climate target (Riahi et al., 2015). For example, the low-carbon share in primary energy (including fossil fuels that are used in combination with CCS) is projected to increase between 2030 and 2050, by 170% in one delay scenario and by 320% in another, while the cost-optimal scenario (reductions from 2010 onwards) shows an increase of approximately 100%, over the same time period.
Put differently, when assuming delay until 2030 as well as unavailability of CCS, only a limited number of model runs find a feasible solution for the 450 ppm CO_2eq[5] target (Riahi et al., 2015). The 2 °C pathways in Kriegler et al. (2014c), which delay action until 2020, also all use negative emissions. Van Vuuren et al. (2015) and Riahi et al. (2015) summarise a few additional challenges related with delaying global mitigation action: reduced flexibility, lock-in, increased costs, and increased climate risks. UNEP (2016) summarised the implications of delaying mitigation as follows: higher emission reduction rates in the medium to long term, less options for stringent reductions available, more lock-in of carbon-intensive infrastructure, greater dependence on negative emissions in the medium to long term, higher mitigation costs, and larger risk of not achieving the 2 °C target (let alone 1.5 °C).

Kriegler et al. (2014a) analysed a different form of delay, looking at so-called staged accession scenarios. In these scenarios, only the EU or the EU and China start early mitigation consistent with achieving 2 °C, and the rest of the world follows between 2030 and 2050. Although these scenarios are unlikely to be consistent with achieving 2 °C (higher probability of exceeding the target), they reduce global warming by 2100 by over 1°C compared to a reference scenario.

Table 2. Summary of timing of reaching net zero CO_2 and greenhouse gas emissions, and emission reductions by 2030 and 2050, for delayed mitigation pathways (starting in 2020).

	Net zero GHG emissions year$^{1)}$		**Change in GHG emissions relative to 2010**$^{2)}$ **levels (top row) / 1990 levels (bottom row)**		
	All GHG	**CO_2**	**2030**	**2050**	**2100**$^{1)}$
Likely chance of staying below 2 °C by 2100 (>66%)	2085 [2080;2100]	2070 [2060;2075]	[-39%;-10%]/ [-19%; 19%]	[-49%;-63%]/ [-32%;-51%]	[-120%;-100%]/ [-127%;-100%]

$^{1)}$ Rounded to the nearest 5 years. Format: median [20th percentile ; 80th percentile]
$^{2)}$ Not provided directly by UNEP (2014), but inferred from Table 2.2 using 49 $GtCO_2eq$ as the 2010 emission level. Range format: [20th percentile ; 80th percentile]
Source: UNEP (2015); UNEP (2014).

In addition to likelihood and start date of cost-optimal mitigation, the metric used to aggregate greenhouse gas emissions to CO_2-equivalent emissions—for example Global Warming Potential (GWP) or Global Temperature change Potential (GTP)— also matters. This issue is not further explored here, but Fuglestvedt et al. (2018) show the impact of different metrics and time horizons on timing of net-zero greenhouse gas emissions (their Figure 2c). They show a shift in the timing by only a few years moving from GWPs from the IPCC's second assessment report (SAR) to the fourth (AR4) or fifth (AR5) assessment report, but up

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[5] Central value within the 430–480 ppm CO_2eq forcing category of IPCC Fifth Assessment report (Clarke et al., 2014)

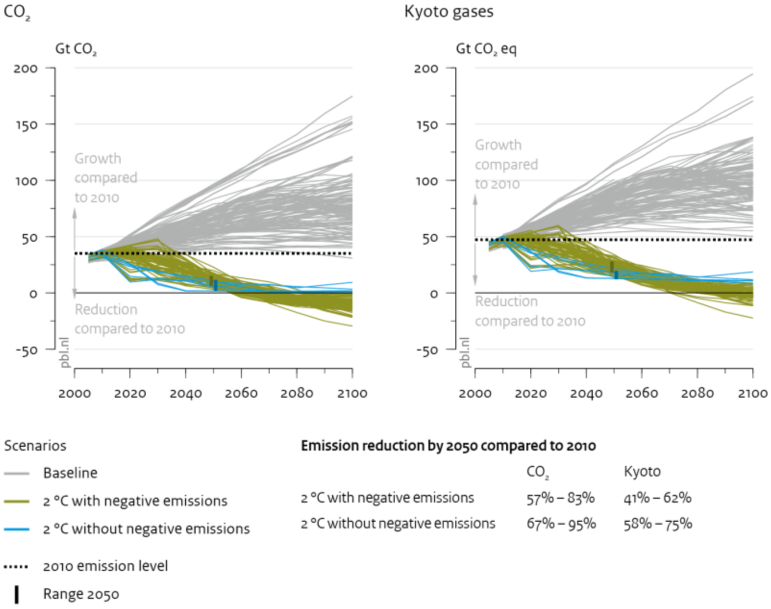
to 20 years earlier phase-out when moving from GWPs to GTPs. Here we use the CO_2-equivalent emissions based on GWPs from AR4 (time horizon of 100 years). The text of the Paris Agreement leaves the choice of metric open, and refers to the common metrics assessed by the IPCC, which are mainly the GWPs.

3.1.2 Literature review: The impact of negative emissions

In most 2 °C scenarios, after reaching net zero greenhouse gas emissions globally, negative emissions are achieved in the second half of the century by the use of so-called negative emissions technologies (see Chapter 4 for an overview). Such negative emissions might be achieved on a large scale, for example, by massive afforestation or reforestation, and/or by combining bioenergy with capture and geological storage of CO_2 (BECCS). Bioenergy combined with CCS has been studied increasingly over the past decade, but uncertainties about its large-scale deployment remain, considering a number of critical barriers (e.g. Fuss et al., 2014; Smith et al., 2016).

Van Vuuren et al. (2015) showed that the use of negative emissions technologies may distinguish pathways (Figure 3). However, far more scenarios with negative emissions are available than scenarios without negative emissions. Generally, excluding the option of negative emissions means both CO_2 and total greenhouse gas emissions need to be reduced more strongly. Cost-optimal (2010) scenarios without negative CO_2 emissions show global greenhouse gas emission reductions of at least 60% to 70% by 2050, and CO_2 emission reductions of 65% to 95% by 2050, compared to 2010 (Van Vuuren et al., 2015). The IPCC's Fifth Assessment Report further shows that scenarios with more net negative emissions (over 20 $GtCO_2$ per year) generally show later and higher greenhouse gas emission peaks, but earlier phase-out years, compared to scenarios with negative emissions below 20 $GtCO_2$ per year (Edenhofer et al., 2014).

Figure 3. Emission pathways for 2 °C, distinguished by the use of negative emissions.



Emission reduction by 2050 compared to 2010

	CO_2	Kyoto
2 °C with negative emissions	57% – 83%	41% – 62%
2 °C without negative emissions	67% – 95%	58% – 75%

Source: IPCC AR5 database

Source: Van Vuuren et al. (2015)

UNEP (2014) also showed that only a small set of scenarios is able to limit warming to below 2 °C without achieving net negative emissions by 2100. However, these scenarios all start stringent, global mitigation before 2020, as also shown in Figure 3, which is no longer considered realistic. Therefore, Riahi et al. (2015) studied scenarios that delay action until

2030, and found that models with large potential for negative emissions could compensate for the delay, keeping the 2 °C target within reach, albeit with higher probability to exceed the target. Limiting or excluding options such as BECCS would make it difficult or even impossible to limit global warming to levels lower than 2 °C. Without exception, all 1.5 °C scenarios available in the literature achieve net negative CO_2 emissions by mid-century, even under stringent mitigation action having started in 2010 (UNEP, 2016). A 'carbon law' presented by Rockström et al. (2017) proposes to halve anthropogenic CO_2 emissions every decade, leading to net zero CO_2 emissions around 2050. This would limit warming to below 2 °C with 66% probability and to below 1.5 °C with 50% probability. In this trajectory, negative emissions through BECCS and LULUCF contribute approximately -20 $GtCO_2eq$ by 2100. Generally, Integrated Assessment Model (IAM) scenarios project negative emissions of 10–20 $GtCO_2eq$ per year in the second half of the century (see also Sections 3.2 and 4.3).

3.1.3 Additional analysis – LIMITS and AMPERE

The additional analysis presented here uses data from the LIMITS and AMPERE projects (Kriegler et al., 2014c; Riahi et al., 2015), which were international cooperation projects. The IAMs covered by these studies are DNE21+, GCAM, GEM-E3, IMAGE, MESSAGE-GLOBIOM, POLES, REMIND-MAGPIE and WITCH.

Box 1. Methodology and scenario characteristics

For this analysis, published 450 ppm CO_2eq mitigation scenarios were used, in which cost-optimal mitigation starts in 2020 (used as default here; presented as 'Delayed 450') or 2030 (presented as 'Delayed 450_2030'), which is considered more realistic than scenarios implementing cost-optimal mitigation from 2010 or 2012.

450 ppm CO_2eq was chosen as it is broadly consistent with a likely (more than 66%) chance to limit global warming to 2 °C. The scenarios that delay cost-optimal mitigation to 2020 (used as default here) have a 66% chance of achieving the 2 °C target (median across four models), but the scenarios that delay cost-optimal mitigation to 2030 only have a 60% chance (median across three models), see Table 3.

Furthermore, scenarios with full technology availability were selected, i.e. no limitations on the use of biomass, CCS, or nuclear, as the effect of technology limitation is not the main question here. Finally, only scenarios with projections until 2100 were used, needed for calculations of phase-out and peak years, but also for calculations of 2030 and 2050 reduction targets consistent with the Paris Agreement long-term goals. For comparison, however, see Appendix III for reduction targets calculated with the set including projections ending in 2050 (POLES and DNE21+, and GEM-E3 with projections up to 2030).

Specifically, the following scenarios remained after this selection: AMPERE2-450-FullTech-HST/LST, LIMITS-RefPol-450 and variants –EE and –PC, and LIMITS-StrPol-450. The AMPERE3-450 scenario was not used as it starts cost-optimal mitigation in 2012 (i.e. it is not in the delayed mitigation towards 450 ppm CO_2eq category). EMF27-450 scenarios were omitted for the same reason. To avoid double counting, only the LIMITS-RefPol-450 scenario was selected in the 'Delayed 2020' category (LIMITS-StrPol-450 is very similar in terms of carbon budgets, temperature change and exceedance probability), while the AMPERE2 scenarios from the 'Delayed 2030' category are shown for comparison. For the POLES model, the scenario results of the GECO 2016 report were used (hereafter referred to as POLES GECO2016), which were only available for the time period 2005-2050 (Kitous et al., 2016).

In addition to selecting scenarios, a few constraints were applied. To filter out different region definitions than EU28 (i.e. Europe in a broader sense, which is not representative for the EU acting as a Party in climate negotiations), projections with 2010 emissions above 1000 Mt CO_2 for the EU were removed. Furthermore, India and EU projections from the MESSAGE model were removed, as the model has a larger South Asia region and an EU region including Turkey. In cases models reported multiple scenarios within the 2030 delayed mitigation 450 ppm CO_2eq category, the mean was taken per model. The GCAM model was excluded as it had a lower probability of achieving the 2 °C objective and higher potential for negative emissions than other models (Riahi et al., 2015). See Appendix I for an overview of remaining models, scenarios and regions covered, and Appendix II for the region definitions.

Note that the 2 °C target was implemented as a radiative forcing target (2.8 W/m^2) in LIMITS, which induces a price on the controlled emissions (all greenhouse gases and other anthropogenic forcing agents), meaning that models had flexibility as to where emission reductions occur to ensure lowest marginal abatement costs. Only Kyoto emissions were priced by most models, while non-Kyoto forcing agents were uncontrolled (Kriegler et al., 2014c). In AMPERE, the target was implemented as a long-term cumulative CO_2 emissions budget (1500 Gt CO_2 for 2000-2100, with different numbers for models that do not include land use emissions or have a time horizon to 2050). Models were instructed to apply the resulting CO_2 price also to non-CO_2 greenhouse gases (Riahi et al., 2015).

Table 3: Scenario characteristics of the scenarios used here (Kriegler et al., 2014a,c; Riahi et al., 2015;Tavoni et al., 2014)

Scenario	**Delay until**	**Cumulative emissions (2010 – 2100)**	**CO_2e concentrations (2100)**	**Probability of achieving 2°C (max)**	**Temperature change (max)**
LIMITS-RefPol-450	2020	700 – 1260 $GtCO_2$ *(fossil fuel and industry CO_2)* 1730 – 2160 $GtCO_2$e *(Kyoto gas)*	450-480 ppm	Around 2/3 (59 – 76%; IMAGE 70%, MESSAGE 60%, REMIND 80%)	1.7 – 1.9 °C
AMPERE2-450-FullTech-HST	2030	1344 (1274 – 1382) $GtCO_2$ *(2005-2100)*	484 (452 – 520) ppm	Median across three models* 53% (full range including GCAM 16% - 72%; MESSAGE 53%, REMIND 61%, WITCH 68%)	2.0 (1.6 – 2.5) °C
AMPERE2-450-FullTech-LST	2030	1335 (1263 – 1379) $GtCO_2$ *(2005-2100)*	488 (455 – 524) ppm	Median across three models* 55% (full range 16% - 72%; MESSAGE 50%, REMIND 61%, WITCH 68%)	2.0 (1.5 – 2.5) °C

** IMAGE scenarios for AMPERE2-450-FullTech-HST and AMPERE2-450-FullTech-LST were not technically feasible.*

Globally, CO_2 emissions are projected to reach net zero between 2060 and 2080, under delayed (2020) mitigation scenarios targeting 450 ppm CO_2eq (assumed to be consistent with a *66% chance* of staying below 2 °C), and by 2070 under delayed (2030) mitigation scenarios (consistent with *55% chance* of staying below 2 °C), according to results from the LIMITS and AMPERE scenario databases (based on four models with projections until 2100 and full data coverage: IMAGE, MESSAGE-GLOBIOM, REMIND-MAGPIE, WITCH). Greenhouse gas emissions, in contrast, are projected to reach net zero after 2090 under delayed (2020) mitigation scenarios and by 2100 under delayed (2030) mitigation scenarios, or show no phase-out at all. Greenhouse gas and CO_2 emissions, however, are projected to peak by 2020 under the delayed (2020) mitigation scenarios and by 2030 under the delayed (2030) mitigation scenarios (Figure 10). All of these scenarios assume no limitation of technologies, and all of them apply negative emissions, mostly in the energy system.

Box 2. What are the net global emission reductions by 2030 and 2050 corresponding to greenhouse gas emissions neutrality?

Table 4, Table 5 and Figure 4 present an overview of the global greenhouse gas and CO_2 emission reductions (including and excluding LULUCF CO_2) by 2030 and 2050 for scenarios having a likely (>66%) chance of limiting global temperature increase to 2 °C during the 21st century. The net global greenhouse gas emissions projections for the world for the full technology[6] *cases of the delayed mitigation 450 ppm CO_2eq scenarios from the AMPERE and LIMITS databases were used, in particular the median estimate over the various model studies with projections until 2100 (see Table 12 in Appendix III for reductions using the full set of models). More specifically: Delayed mitigation pathways towards 450 ppm CO_2eq, i.e. limited action until 2020 and cost-optimal mitigation afterwards in order to achieve a CO_2-equivalent concentration level of 450 ppm by 2100.*

Table 4: Projected global greenhouse gas emissions (including LULUCF CO_2) by 2030 and 2050, relative to 2010, in delayed mitigation 450 ppm CO_2eq scenarios (negative numbers denote a reduction).

	2030	**2050**
Delayed (2020)	**%**	**%**
Mean [min; max]	-18 [-39; -7]	-58 [-65; -47]
Median [10th percentile; 90th percentile]	**-13** [-32; -9]	**-59** [-63; -51]
Delayed (2030)	**%**	**%**
Mean [min; max]	13 [12; 15]	-52 [-61; -43]
Median [10th percentile; 90th percentile]	14 [12; 15]	-51 [-59; -45]

For comparison to 1990 levels: GHG emissions have increased from 38 GtCO_2eq in 1990 to 51 GtCO_2eq in 2010 (EDGAR database, JRC/PBL, 2014).
Source: LIMITS and AMPERE databases (Kriegler et al., 2014c; Riahi et al., 2015)

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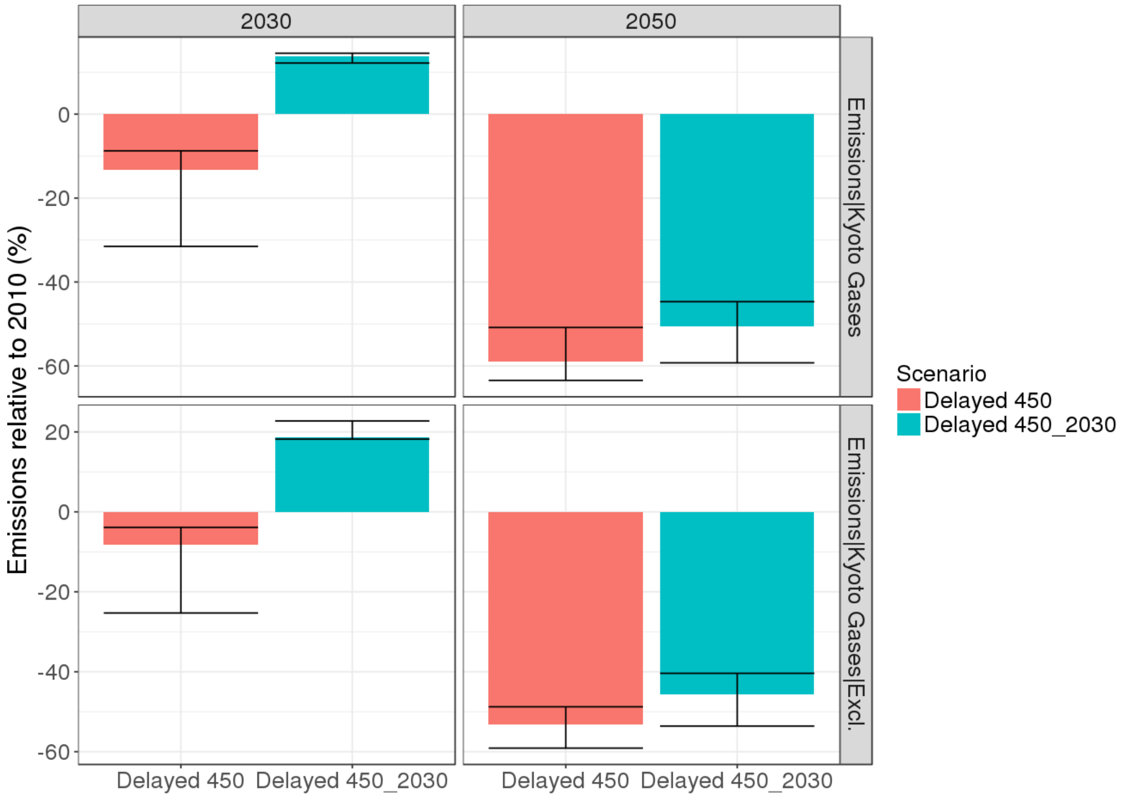
[6] The full portfolio of technologies is available and may scale up successfully to meet the concentration target.

Figure 4: Projected global greenhouse gas emissions (upper: including LULUCF CO_2, lower: excluding LULUCF CO_2) by 2030 and 2050, relative to 2010, in delayed mitigation 450 ppm CO_2eq scenarios (left: 2020, right: 2030).



Negative numbers denote a reduction. Bar: median, error bar: 10th – 90th percentiles.

Table 5: Projected global CO_2 emissions (including LULUCF CO_2) by 2030 and 2050, relative to 2010, in delayed mitigation 450 ppm CO_2eq scenarios (negative numbers denote a reduction).

	2030	**2050**
Delayed (2020)	**%**	**%**
Mean [min; max]	-22 [-47; -8]	-76 [-84; -62]
Median [10th percentile; 90th percentile]	-17 [-39; -10]	-80 [-83; -66]
Delayed (2030)	**%**	**%**
Mean [min; max]	16 [14; 21]	-69 [-80; -62]
Median [10th percentile; 90th percentile]	15 [14; 20]	-64 [-77; -62]

For comparison to 1990 levels: CO_2 emissions have increased from 22 $GtCO_2$ in 1990 to 34 $GtCO_2$ in 2010 (EDGAR database, JRC/PBL, 2014).
Source: LIMITS and AMPERE databases (Kriegler et al., 2014c; Riahi et al., 2015)

3.2 What does greenhouse gas emissions neutrality mean, with respect to global CO_2 and non-CO_2 emissions?

Greenhouse gas emissions neutrality does not imply full decarbonisation, as the remaining emissions of CO_2 in the transport, industry and building sectors, and of non-CO_2 greenhouse gases, mostly in agriculture, can be compensated for by negative emissions from LULUCF sinks (mainly forests) and through the use of biomass in energy production coupled with Carbon Capture and Storage (BECCS).

Three major categories of mitigation actions can be identified for achieving net zero greenhouse gas emissions (Government of the United States, 2016):

1. Decarbonising the energy system, by decarbonising electricity and using low-carbon fuels in transportation, buildings, and industry;
2. Reducing non-CO_2 emissions (CH_4, N_2O and F gases), which come from fossil fuel production, agriculture, waste, and refrigerants; and
3. Sequestering carbon, by increasing carbon stocks on land (forests and soils) and by deploying technologies such as BECCS, which can result in negative emissions.

This implies that extra efforts in one area (sector, greenhouse gas) can compensate for less action in another area, for example because of technical limitations.

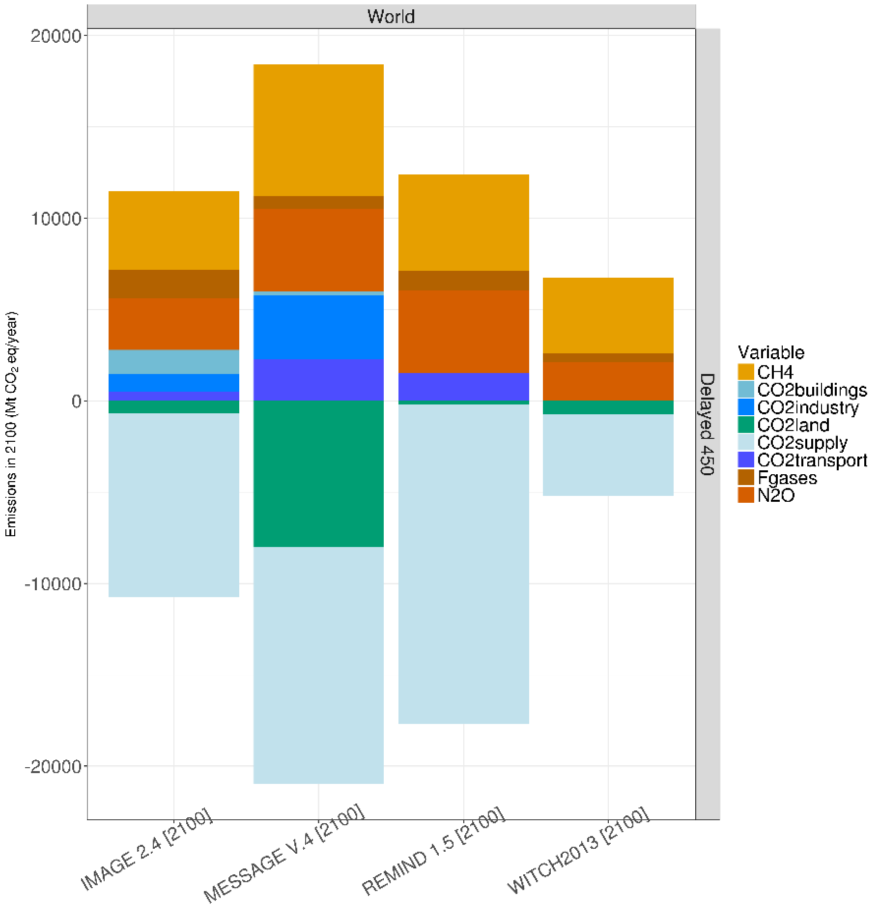
Approximately 900 mitigation scenarios from IAMs have been evaluated in the IPCC Fifth Assessment Report (Edenhofer et al., 2014). Main findings regarding the contributions of CO_2, non-CO_2 and negative emissions are as follows:

1. For decarbonising the *energy system*, the share of low-carbon energy supply (renewables, nuclear energy, fossil energy with CCS and BECCS) triples to quadruples by 2050, relative to 2010, under scenarios reaching 450 to 500 ppm CO_2eq by 2100. Luderer et al. (2017) found that wind and solar power are generally projected to contribute substantially to the decarbonisation of the power sector, accounting for over half of electricity supply in 2 °C-consistent scenarios. They further concluded that variable renewable energy sources would need higher shares in electricity supply if nuclear power or CCS are excluded. Options to decarbonise *transport* include using electric, hydrogen and fuel-cell light-duty vehicles, low-carbon fuels, improving vehicle and engine performance, behavioural change (modal shift), investments in infrastructure, and avoiding journeys. In the *building* sector, net zero-energy buildings in both new constructions and retrofits and behavioural changes offer key mitigation options. For decarbonising *industry*, mitigation options beyond energy efficiency are needed, including recycling, product innovations and reducing service demand.
2. Next to decarbonising the energy system, these scenarios see a critical role for mitigation within the land system. Next to afforestation and BECCS (category 3), agricultural productivity improvement plays a role. F-gas emissions could be reduced by the replacement of HFCs, recycling refrigerants, and repairing leaks in industry.
3. Many scenarios that temporarily overshoot the target (e.g. 450 ppm CO_2eq by 2100) rely heavily on BECCS and/or afforestation in the second half of the century.

Figure 5 gives a breakdown of greenhouse gas emissions by the end of the century (scenarios from the LIMITS and AMPERE databases, with 4 models providing projections of greenhouse gas emissions up to 2100). For the delayed mitigation 450 ppm CO_2eq scenarios, MESSAGE-GLOBIOM and REMIND-MAGPIE project phase-out years for greenhouse gas emissions around 2090, while the IMAGE and WITCH models project no phase-out during the 21st century. Remaining emissions in the phase-out year, similar to those under the optimal and delayed mitigation scenarios, are projected to come from 1) the energy system (demand sectors transport, industry and, to a smaller extent, buildings) and 2) non-CO_2 greenhouse gases (CH_4, N_2O, and F gases). All models show negative emissions (category 3) in energy supply, achieved through carbon capture and storage. They further show negative emissions in LULUCF (afforestation), although to various degrees (while MESSAGE-GLOBIOM realises a significant part of projected negative emissions through LULUCF—i.e. afforestation, REMIND-MAGPIE has a stronger preference for BECCS, with much lower negative LULUCF emissions).

Remaining CO_2 emissions from transport vary more across models than other sectoral emissions. This relates to different ways the models project final energy demand in transportation to be met: while MESSAGE-GLOBIOM projects relatively large use of gases, IMAGE projects use of gases to be almost phased out. IMAGE further shows a stronger increase in hydrogen use than other models. IMAGE projects a strong decrease in the use of liquids (especially oil) and REMIND-MAGPIE also projects a decrease, while MESSAGE-GLOBIOM shows more or less stable liquids use. As such, IMAGE decarbonises transport more than other models do. All models project further electrification of transport, with transport electricity demand increasing most in models that project larger total final energy use in transportation (MESSAGE-GLOBIOM, REMIND-MAGPIE).

Figure 5. Breakdown of emissions ($MtCO_2eq$) in 2100 (qualitatively similar to emissions in the phase-out year for greenhouse gas emissions), for delayed mitigation 450 ppm CO_2eq scenarios.



Positive numbers denote remaining emissions of CH_4, N_2O, F gases, and CO_2 in industry ('CO2industry'), buildings ('CO2buildings') and transport ('CO2transport'), while negative *numbers denote negative emissions in energy supply[7] ('CO2supply') and land use[8] ('CO2land'). Note that REMIND-MAGPIE did not report CO_2 emissions from the demand sectors (buildings, industry, agriculture), and none of the models reported CO_2 emissions from agriculture. Source: PBL calculations are based on the LIMITS and AMPERE databases* (Kriegler et al., 2014c; Riahi et al., 2015).

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[7] 'CO_2supply' includes 'carbon dioxide emissions from power and heat generation, other energy conversion (e.g. refineries, synfuel production), resource extraction and energy transmission and distribution (e.g. gas pipelines)'. Negative emissions in this sector results from the use of (BE)CCS.

[8] 'CO2land' means 'net carbon dioxide emissions from all categories of land use and land-use change (e.g., pasture conversion, deforestation, afforestation, reforestation, soil management, etc.)'

3.3 When would national and regional greenhouse gas emissions need to reach net zero, under 2 °C scenarios?

Regional projections of phase-out years depend strongly on how negative emissions achieved through BECCS are allocated: to the region producing the biomass, or to the region applying it with CCS? Using the latter definition (consistent with the IAM models), the earliest achievement of net zero greenhouse gas emissions occurs in 2060, and of net zero CO_2 emissions in 2050, for some regions, while most regions are projected to reach net zero later, based on the analysis of model scenarios of the LIMITS and AMPERE projects. For regions with larger shares of non-CO_2 emissions and/or less potential to create negative emissions, this moment occurs later in time. Differences in land-use accounting methods strongly affect the year greenhouse gas emissions neutrality is reached. As indicated earlier, uncertainty in land-use related CO_2 emissions is large, while this is confounded by the different definitions that are used. The EU, China and the United States report carbon sinks for managed forests, which are projected to remain more or less the same in the future. Models, however, consider this to be a natural CO_2 sink caused by carbon fertilisation. This discrepancy can be removed by harmonising definitions. It is possible to get some idea of the impact of this definition of 'harmonisation' by, in this case, adding the absolute emissions difference in 2010 between the inventory data and the model data to the model projections. This leads to shifting the absolute values of the emission projections up or down, without changing the trend. The shift in LULUCF CO_2 emissions explored here leads, on average, to projected phase-out dates for greenhouse gases and CO_2 that are approximately 5 to 15 years earlier, as 2010 emission levels as calculated by models are generally higher than those from officially reported emissions data. Harmonising the model projections towards the countries' land use emissions estimates results in net zero or negative emissions being achieved sooner. The shift especially affects projected phase-out years for countries where LULUCF emissions play an important role (e.g. China, the EU and the United States, with reported carbon sinks). At the same time, also uncertainty still plays a large role. The linear shift also leads to a convergence of the phase-out years for OECD countries, including the EU as a group, to around 2050–2070, which is earlier than for most of the non-OECD countries. Low-income countries, such as India, have projected phase-out years at the end of the century.

In the previous sections, phase-out years and contributions of different greenhouse gases were described at the global level. However, these may differ at the regional level, with some countries phasing out greenhouse gas emissions at an earlier point in time than other countries.

The IAM scenarios discussed here assume globally cost-optimal emission reductions to reach 2 °C, starting in 2010 (older literature), 2020, or 2030. As a result, these scenarios assume that emissions are reduced in the regions and sectors where they are cheapest to be reduced. This does not say anything on who *pays* for these emission reductions. Generally, these scenarios show earlier phase-out dates (by when emissions reach net zero) for countries with a large potential for emission reduction and/or negative emissions, in particular related to the potential of the land use sector to generate negative emissions, be it directly in the form of a sink, or indirectly through BECCS. For example, many models assume that avoiding deforestation and enhancing afforestation can be achieved at low prices and therefore assign early reductions to the Latin American region. In addition, regional projections of phase-out years depend strongly on how negative emissions achieved through BECCS are allocated: to the region producing the biomass, or to the region applying it with CCS? In IAMs, the latter is generally used as definition, which we, therefore, also use here. Future research could explore the implications of different allocation rules for regional neutrality projections.

Höhne et al. (2015) distinguished between a likely and a medium chance of achieving the 2 °C target under cost-optimal (2010) pathways, and concluded that, for a likely chance, regional CO_2 and greenhouse gas emissions would need to reach net zero roughly 10 years earlier than for a medium chance. For both a likely and a medium chance, the OECD90 and Latin America regions are projected to be the first to phase out CO_2 emissions (2050–2060), followed by Economies in Transition, Middle East and Africa, and Asia. Lowering the likelihood from likely to medium matters especially for the Middle East and Africa (median phase-out of CO_2 by around 2080 instead of 2065) and Asia (by 2095 instead of 2070). For all greenhouse gases, moving from a medium to a likely chance affects the phase-out year for especially the OECD90 countries (by 2065 instead of 2085) and the Economies in Transition (by 2080 instead of 2100).

Although there are many studies about the effect of delaying cost-optimal emission reductions on a global level, not many address regional or even national (cost-effective) emission pathways that are based on global 2 °C scenarios involving delayed emission reductions. Certain multi-model studies (ROSE, EMF) explore non-idealised international implementation based on specific assumptions about delayed and limited regional participation in emission reductions. The LIMITS multi-model comparison study (e.g. Tavoni et al., 2014 and Van Sluisveld et al., 2013) analysed the impact of full and partial implementation of the countries' reduction proposals (pledges) for 2020, as part of the Cancun Agreements, in the context of having a likely chance of achieving the 2 °C target. It looks at regional mitigation strategies of five major economies (China, EU, India, Japan, and United States). In the multi-model comparison AMPERE project, the delayed participation was extended until 2030, applying cost-effective reductions towards achieving the 2 °C objective beyond 2030. Table 6.1 of the IPCC's Fifth Assessment Report (AR5) (Clarke et al., 2014) gives an overview of delayed and limited participation studies. On regional cost effects of delay, the IPCC AR5 (Clarke et al., 2014) concludes that the higher costs of delayed action generally fall on the early actors. However, countries that delay mitigation only benefit from lower costs in the short term. In the longer term, they mostly face higher costs.

The MILES project is the first study that has analysed mitigation scenarios towards staying below the global temperature increase of 2 °C for a much larger group of countries and regions, based on the full implementation of the countries' conditional and unconditional 2020 pledges (Van Soest et al., 2017a). It uses the scenario databases from earlier multi-model comparison studies (LIMITS, AMPERE, EMF). This section further presents additional analysis, using the LIMITS and AMPERE databases as applied regionally in MILES.

It should be noted that, in their spatial aggregation, not all models in the LIMITS and AMPERE projects include all of the countries and regions selected for the graphs in this section. For some countries and regions, therefore, the results are based on a lower number of models. Other reasons for lower numbers of models are that (i) some models do not have projections up to 2100, as their time horizon is 2050, and (ii) some models do not have the sectoral aggregation shown here. Therefore, the results for countries that are only covered by two models should be seen as indicative.

Additional analysis using the LIMITS and AMPERE databases shows that a phase-out of greenhouse gas emissions is projected to occur earliest in Latin-American countries (after

2060), followed by OECD90 (including the EU), reforming economies[9], and rest of the world (after 2070). Asia, Middle East and Africa show either no phase-out at all or at the end of the century. CO_2 emissions are phased out earlier, starting in Latin America (2050–2070), rest of the world (2050), and reforming economies (2050), followed by OECD90 (including the EU) (2060–2070), and Middle East and Africa (2060–2100). Asia shows the latest phase-out of CO_2 emissions (after 2070 or not at all).

Figure 6 shows regional phase-out years for all greenhouse gases versus CO_2 for scenarios having a likely (>66%) chance of limiting global warming to 2 °C (see also Figure 4 in Höhne et al., 2015). While regional differences can be observed, greenhouse gas emissions are generally projected to reach net zero after 2060 in both delayed and optimal mitigation 450 ppm CO_2eq scenarios (Figure 6). For CO_2 emissions, delayed (2020) mitigation scenarios show a phase-out generally after 2050. Optimal mitigation scenarios allow for a somewhat later phase-out of CO_2 emissions. Regional differences are most pronounced in the delayed mitigation scenario, with China and the EU showing a slightly later phase-out than other countries. In OECD countries as a group, greenhouse gas emissions are projected to peak immediately and reach net zero between 2070 and 2100, while those in the Middle East and Africa are allowed to peak between 2020 and 2030 and reach net zero after 2090.

Figure 7 shows the projected phase-out years for all greenhouse gases relative to the global average, showing that OECD90 (except EU member states) and Latin America generally have earlier phase-out years than the global average and the EU due to relatively cheap negative emissions potential, Reforming economies are similar to or earlier than the global average, Middle East and Africa are similar to or later than global average (due to growing populations and relatively high mitigation costs, especially in energy exporting regions), and Asia is generally later than global average, with a large spread for China and India.

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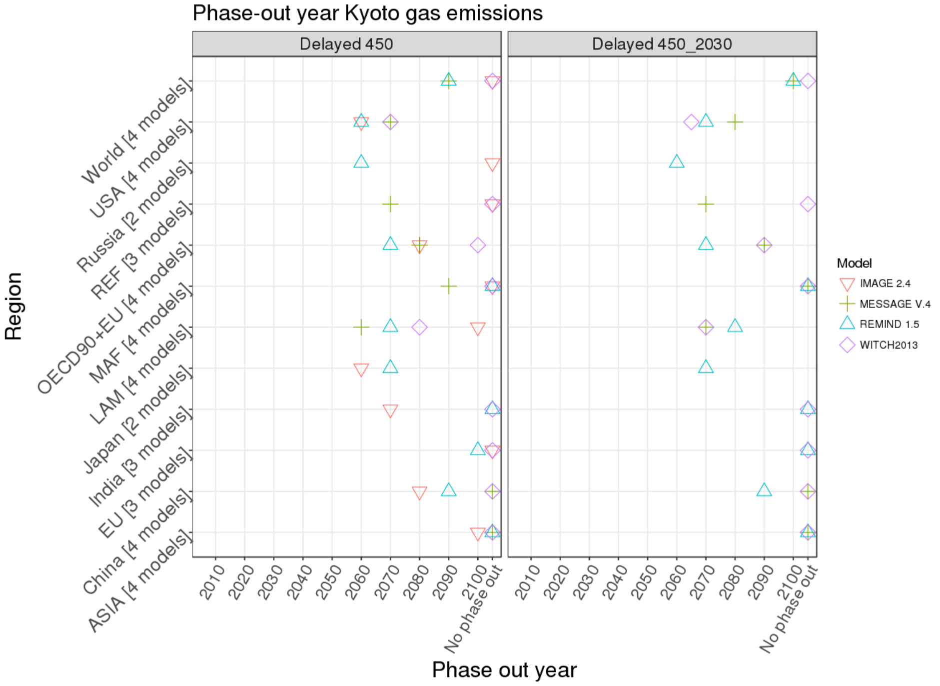
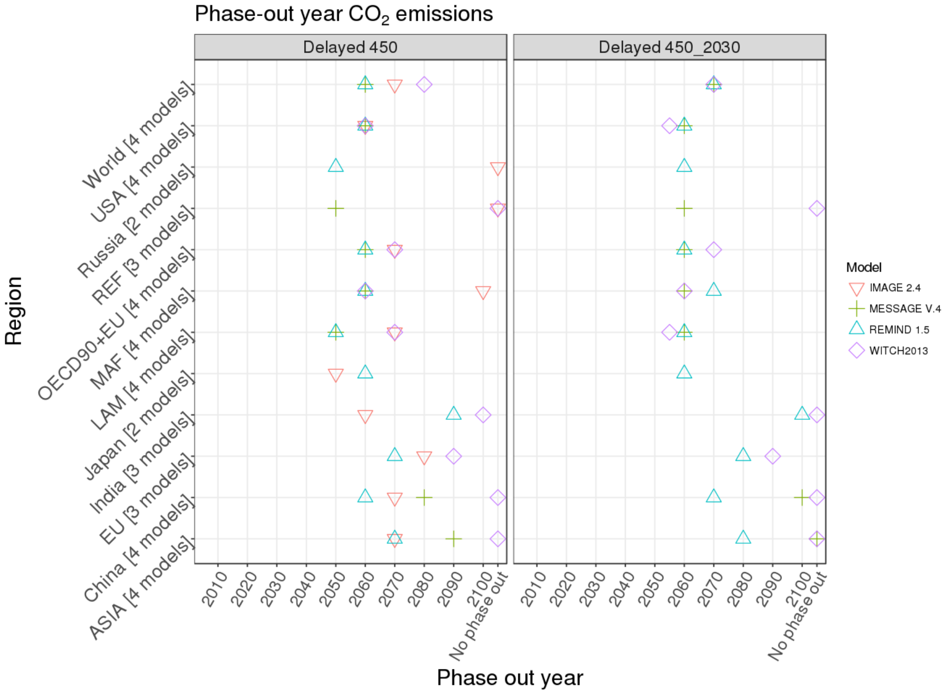
[9] Countries from the Reforming Economies of the Former Soviet Union.

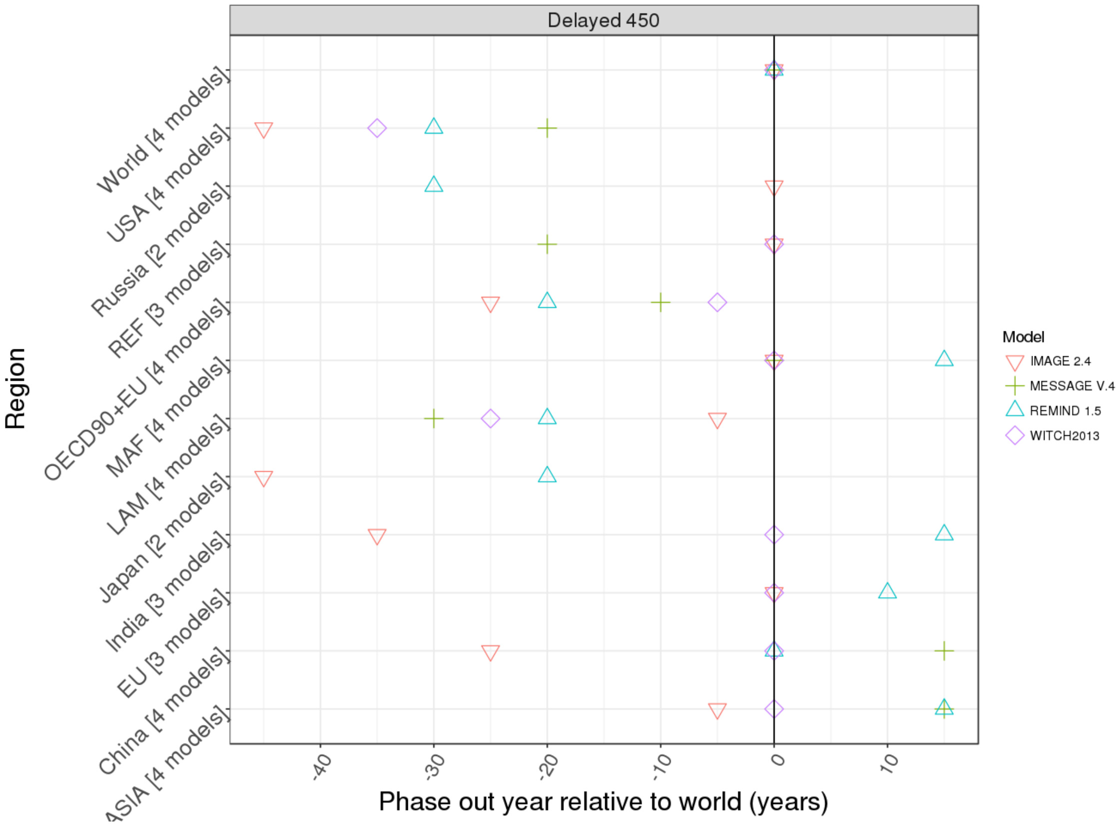
Figure 6. Regional phase-out years (when emissions reach net zero) for greenhouse gases (upper graph) and CO_2 (lower graph), in delayed mitigation 450 ppm CO_2eq scenarios (2020: left and 2030: right), based on the LIMITS and AMPERE databases (Kriegler et al., 2014c; Riahi et al., 2015)





Note that more models report CO_2 emissions than greenhouse gas emissions. Not all models include all of these countries in their spatial aggregation, implying that for many countries, the results were based on a lower number of models. Only results for countries covered by at least two models are shown. No IMAGE projections for delayed (2030) mitigation scenarios were available.

Figure 7: Regional phase-out years for greenhouse gases relative to the same model's global average, in delayed mitigation 450 ppm CO_2eq scenarios (2020), based on the LIMITS and AMPERE databases (Kriegler et al., 2014c; Riahi et al., 2015).



Negative numbers indicate earlier phase-out, positive numbers indicate later phase-out, and 0 indicates equal phase-out years for the region and the global average. Only results for regions covered by at least two models are shown.

Box 3: Harmonisation

The national and regional emission projections by integrated assessment models, generally, show historical emissions that differ from the officially reported emissions data from countries (national inventories) (Nakicenovic and Swart, 2000; Rogelj et al., 2011). In particular, the discrepancies between land-use related emissions based on officially reported data and the IAM data are large, due to the differences in estimating the " anthropogenic" land-use emissions (Grassi et al., 2017). More specifically, integrated assessment models define anthropogenic land-use emissions based on direct human-induced effects (land-use changes and harvesting) on managed and unmanaged land, whereas national inventories use the IPCC 2006 Guidelines and include, in addition to these human-induced effects on land, also the sinks of managed land based on indirect human-induced effects (such as CO_2 fertilisation), and natural effects (Grassi et al., 2017). None of the scenarios in the literature incorporate officially reported data for land-use related emissions. The method for resolving this discrepancy in the historical land-use related emissions is called 'harmonisation'.

So far, the emission projections presented in this report were not harmonised. One methodology for harmonisation, the so-called simple 'offset' harmonization, is adding the absolute emissions difference in 2010 between the inventory data and the model data to the model projections (see Figure 9). Harmonising the model projections in such a way, i.e. shifting the absolute values of the model projections, implies that the starting points of the *scenarios become the same as the national inventories, without changing the trend of the projections. This is especially useful in the case of models using different definitions, meaning they may miss the sinks of managed forests. For those countries with reported sinks, harmonisation of LULUCF emissions/removals to national inventories is expected to have an effect on the timing of reaching net zero emissions (phase-out dates) by shifting the absolute values of the emission projections up or down. Harmonising the model projections also implies a change of the original emission projections.*

Table 6 and Figure 8 show the impact of a simple 'offset' harmonisation on projected phase-out years in major emitting countries, applying an absolute correction throughout the century based on the modelled 2010 emission levels minus historical data for 2010 emission levels (see also Figure 9 for more detailed results of individual models). The historical GHG emissions data were taken from latest inventories, many of which have been submitted to the UNFCCC in 2017, as described in detail in Kuramochi et al. (2016)[10]*. Here we focus on one case in addition to the default of no harmonisation: harmonisation of only land use, land-use change and forestry* CO_2 *(LULUCF* CO_2*) emissions/removals, adding unharmonised greenhouse gas emissions excluding LULUCF to calculate total greenhouse gas emissions (for more details, see Appendix IV).*

Harmonisation of the EU emissions is complicated by the fact that most models cover Europe as a region, and not the EU28, so by definition these models' 2010 emissions are higher than the emissions reported for the EU28. Harmonisation of greenhouse gas emissions excluding LULUCF using the offset method would have a large effect, due to the artefact that models do not have the EU28 as a region. All models have larger 2010 emissions than historical data (the difference ranges from 600 to 1250 $MtCO_2eq$*). Therefore, we only show the cases no harmonisation and harmonisation of LULUCF* CO_2 *emissions only.*

In summary, the central cases of this report assume no harmonisation, which has the advantage of staying as close to the original projections as possible, and offset harmonisation of LULUCF emissions/removals.

In general, the harmonisation applied here leads to projected phase-out years for greenhouse gases and CO_2 *that are approximately 5 to 15 years earlier, as 2010 emission levels as calculated by models are generally higher than those from officially reported emissions data, in particular for LULUCF emissions (Grassi et al., 2017)*[11]*. It shifts the absolute value of model projections down (keeping the trend the same), resulting in earlier occurrence of (below) zero emissions. However, regional differences exist. For the EU, China, Russia, and the United States, harmonisation gives earlier phase-out years. For the United States, it also results in smaller spread across models.*

Harmonisation of LULUCF emissions only is especially interesting for China, India, Russia and the United States, where these emissions play an important role. In China, India, Russia and United States, models show either positive LULUCF CO_2 *emissions or negative emissions, the amount of which is smaller than the reported carbon sink, as historical data shows (approximately -421* $MtCO_2$ *for China, -175* $MtCO_2$ *for India, -950* $MtCO_2$ *for United States and -651* $MtCO_2$ *for Russia). As such, harmonisation leads to earlier projected phase-out*

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[10] The historical 2010 emissions for the G20 countries are based on the Common Reporting Format 2017 (2016 inventory for the USA and Canada) to the UNFCCC (2017) for Annex I countries, and the national GHG inventory data reported in most recent Biennial Update Reports (BURs) submitted to the UNFCCC (2017) (when available), EDGAR database (JRC/PBL, 2014) and FAOSTAT data (land-use emissions) for non-Annex I countries. For World, a 2010 LULUCF emission level of 0 Gt CO_2 was assumed for illustrative purposes (based on Grassi et al., 2017).

[11] For global LULUCF emissions/removals, Grassi et al. (2017) found a difference of around 3 $GtCO_2$ in 2010 between the global emissions estimates by the IPCC AR5 and the global estimate based on the national country reports following the IPCC Guidelines for National Greenhouse Gas Inventories.

years. Harmonisation leads to a convergence of the phase-out years for OECD countries, including the EU as a group, to around 2050–2070, which is earlier in time than for most of the non-OECD countries. Low-income countries, such as India, remain having projected phase-out years at the end of the century.

More research on the differences between national inventories and emission levels used in model projections is required (Grassi et al., 2017). Most notably concerning how LULUCF greenhouse gas emissions and removals are included in models versus how they are reported under national inventories, to improve understanding of the quantitative effect of harmonisation on required emission reductions.

Table 6. Projected regional phase-out years (median estimates) for greenhouse gas emissions (upper table) or CO_2 emissions only (lower table), under delayed mitigation scenarios (2 °C, cost-optimal allocation of reductions implemented after 2020), without harmonisation (column 1) and with harmonisation to CO_2 emissions/removals from LULUCF (column 2) (adding unharmonised greenhouse gas/CO_2 emissions excluding LULUCF CO_2 to calculate all greenhouse gas/CO_2 emissions). Only regions that are covered by at least two models are shown here (these numbers should be interpreted with care, due to the limited number of models with varying coverage of LULUCF emissions). See Appendix IV for indicative results on aggregated regions. Source: analysis of this study.

Phase-out year* for all greenhouse gas emissions

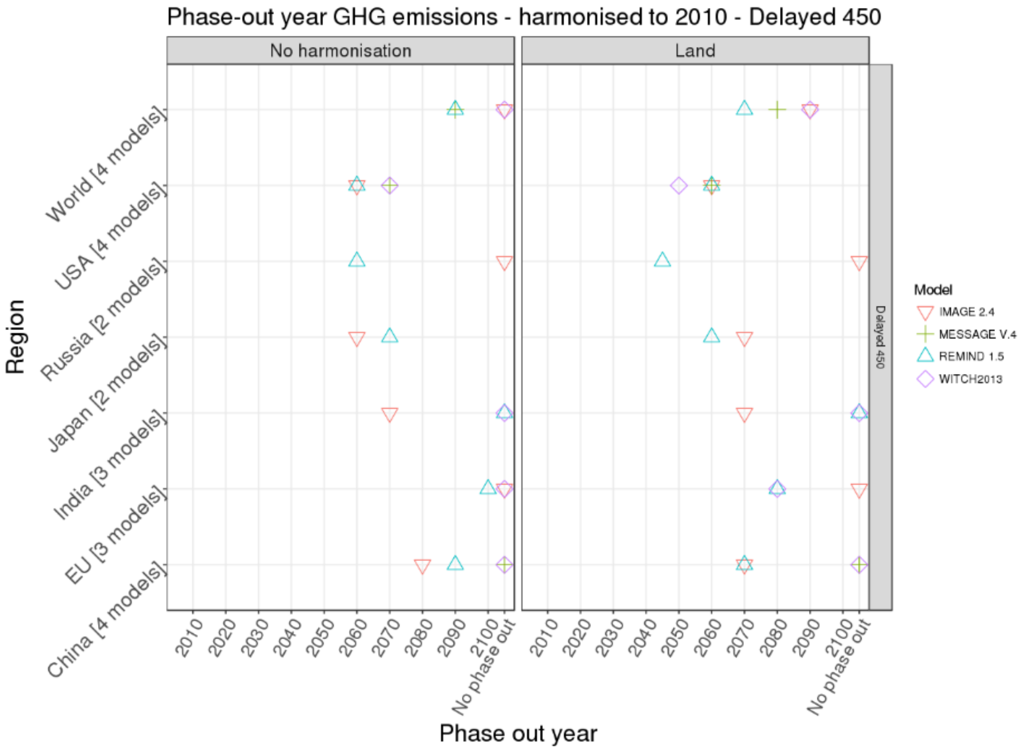
Country/region [no. of models]	No harmonisation	Harmonisation of CO_2 emissions from LULUCF	Phase-out year relative to world (no harmonisation)
China [4]	2100	2090	Same
EU [3]	No phase-out	2080	Later
India [3]	No phase-out	No phase-out	Later
Japan [2]	2065	2065	Earlier
Russia [2]	2085	2075	Earlier
United States [4]	2065	2060	Earlier
World [4]	2100	2085	-

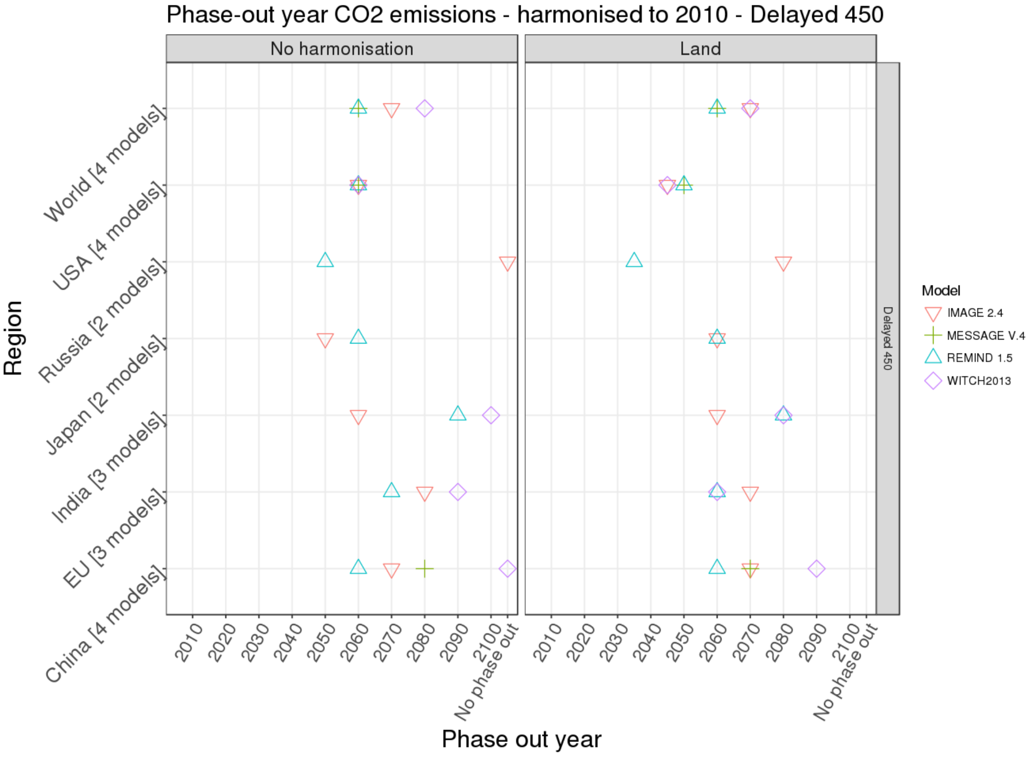
Phase-out year* for CO_2 emissions

Country/region [no. of models]	No harmonisation	Harmonisation of CO_2 emissions from LULUCF	Phase-out year relative to world (no harmonisation)
China [4]	2075	2070	Later
EU [3]	2080	2060	Later
India [3]	2090	2080	Later
Japan [2]	2055	2060	Earlier
Russia [2]	2080	2055	Later
United States [4]	2060	2045	Earlier
World [4]	2065	2065	-

* Numbers should be interpreted with care, as models generally report their emission projections with 10-year time steps.

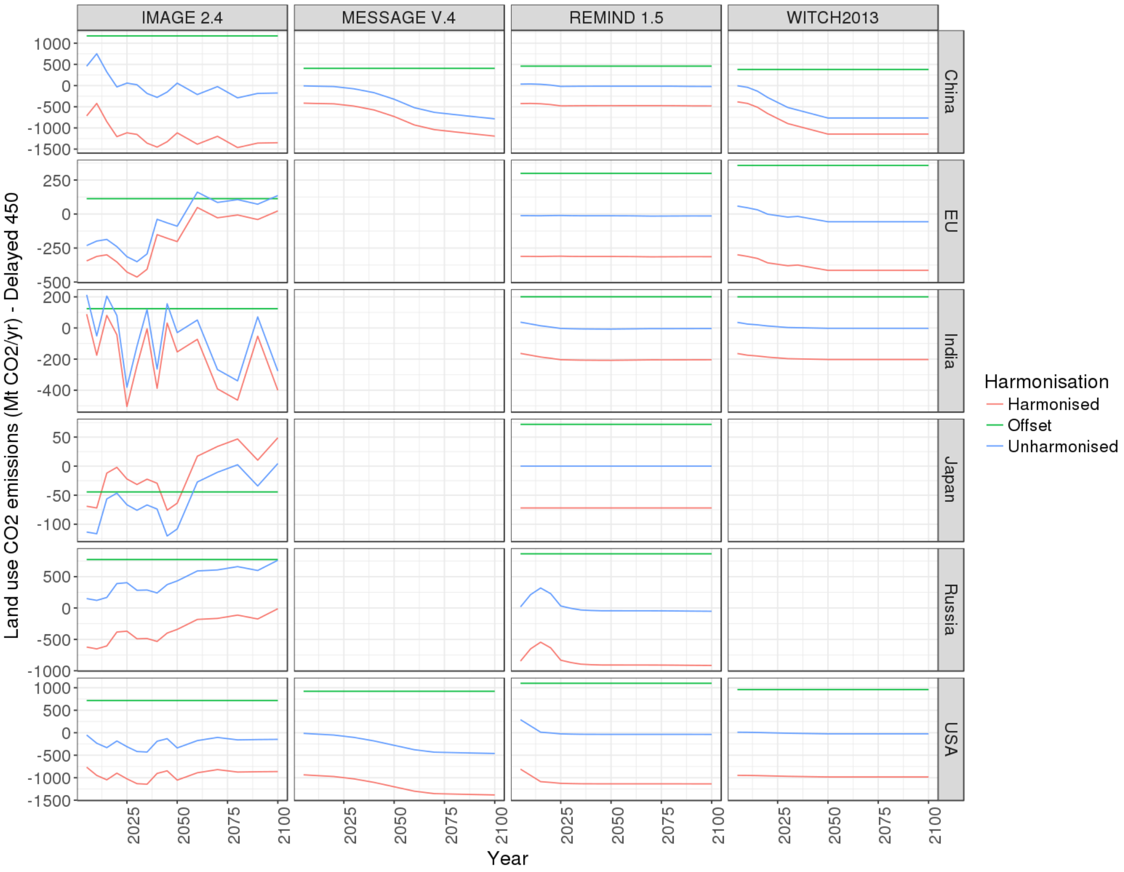
Figure 8. Effect of the harmonisation method on the phase-out year for greenhouse gases (upper figure) and CO_2 (lower figure), in delayed mitigation 450 ppm CO_2eq scenarios.

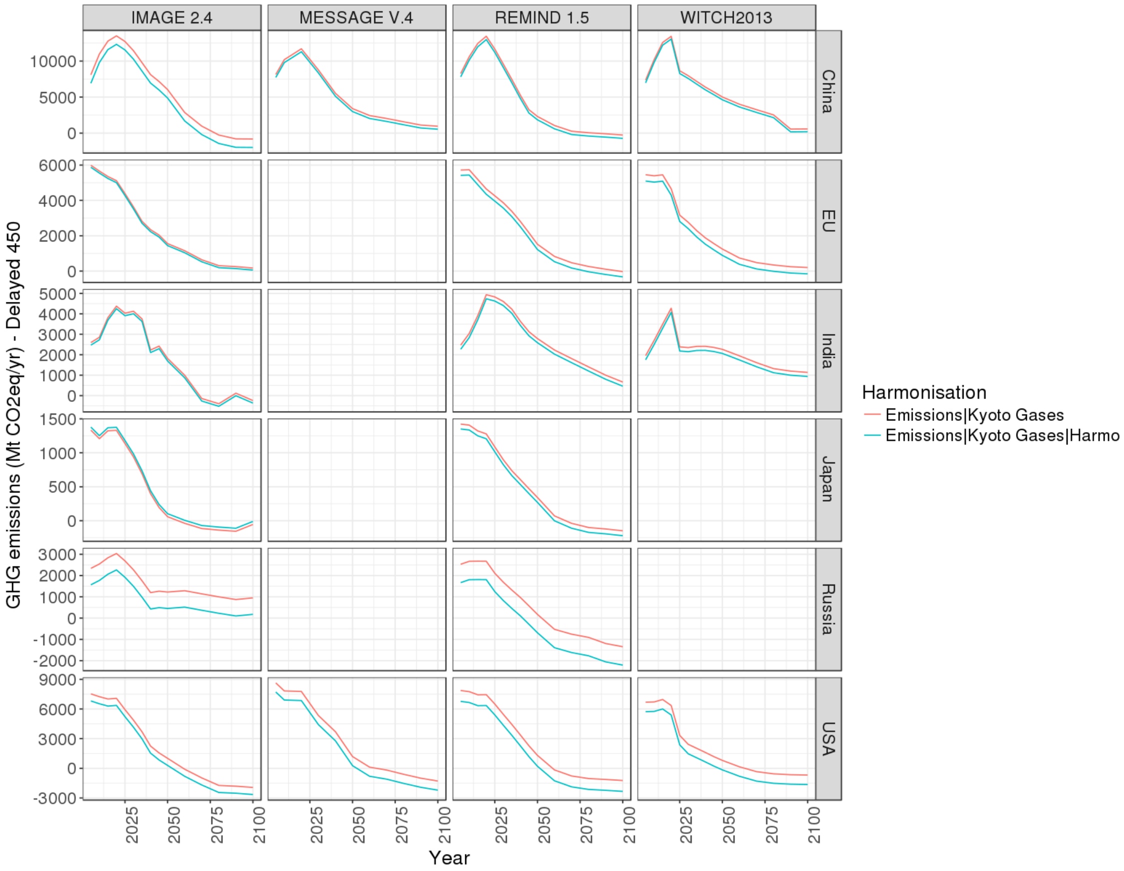




In both graphs, left: no harmonisation, right: LULUCF emissions/removals harmonised to 2010 levels (adding unharmonised greenhouse gas [CO_2] emissions excluding LULUCF CO_2 to calculate total greenhouse gas [CO_2] emissions). Source: LIMITS and AMPERE databases (Kriegler et al., 2014c; Riahi et al., 2015). *For harmonisation of total greenhouse gas* *emissions, historical data from Kuramochi et al. (2016) were used, and the same absolute correction level (modelled 2010 emission levels minus historical data for 2010 emission levels) was applied throughout the century. For harmonisation of CO_2 emissions, historical data from UNFCCC (2017) were used. Note that Brazil's projected greenhouse gas phase-out year, excluding LULUCF harmonisation, in reality will be 2070; it is shown as 2015 because that is the first year with (momentarily) negative emissions. Not all models include the same number of countries in their spatial aggregation, implying that for many, the results are based on a lower number of models. Only results for countries covered by at least two models are shown.*

Figure 9. Effect of harmonisation on the emission pathways for land use CO_2 (upper figure) and greenhouse gases (lower figure), in delayed mitigation 450 ppm CO_2eq scenarios, per model and region.

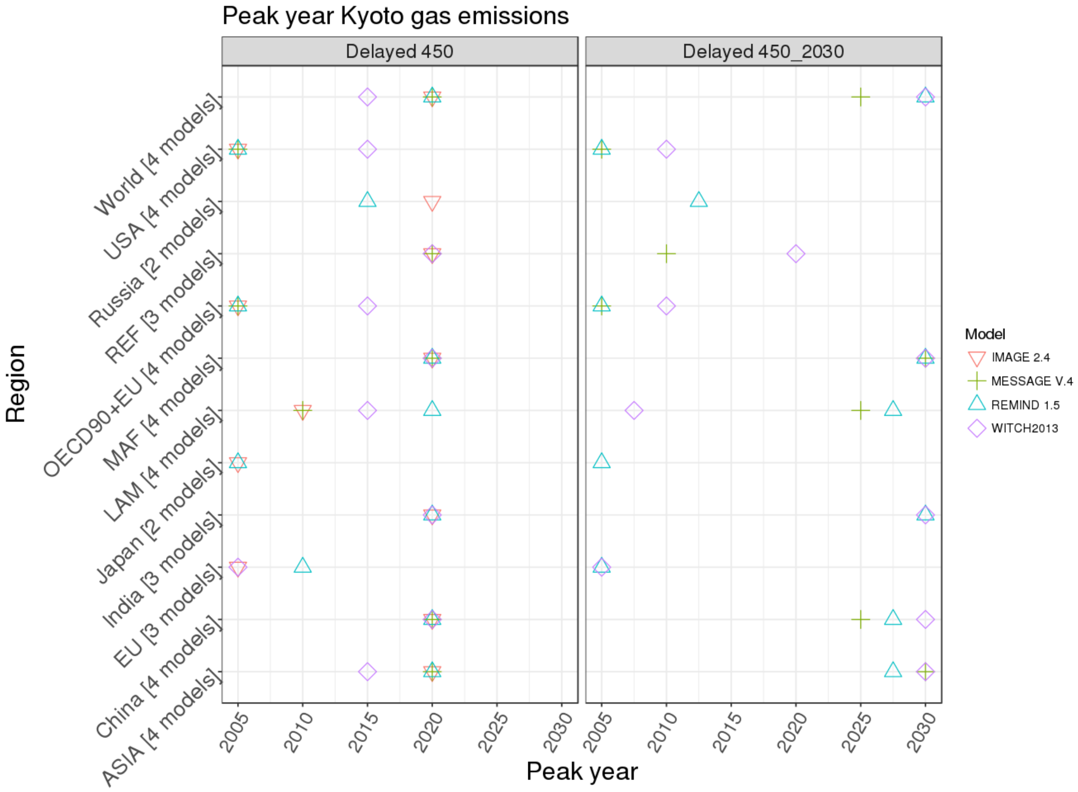


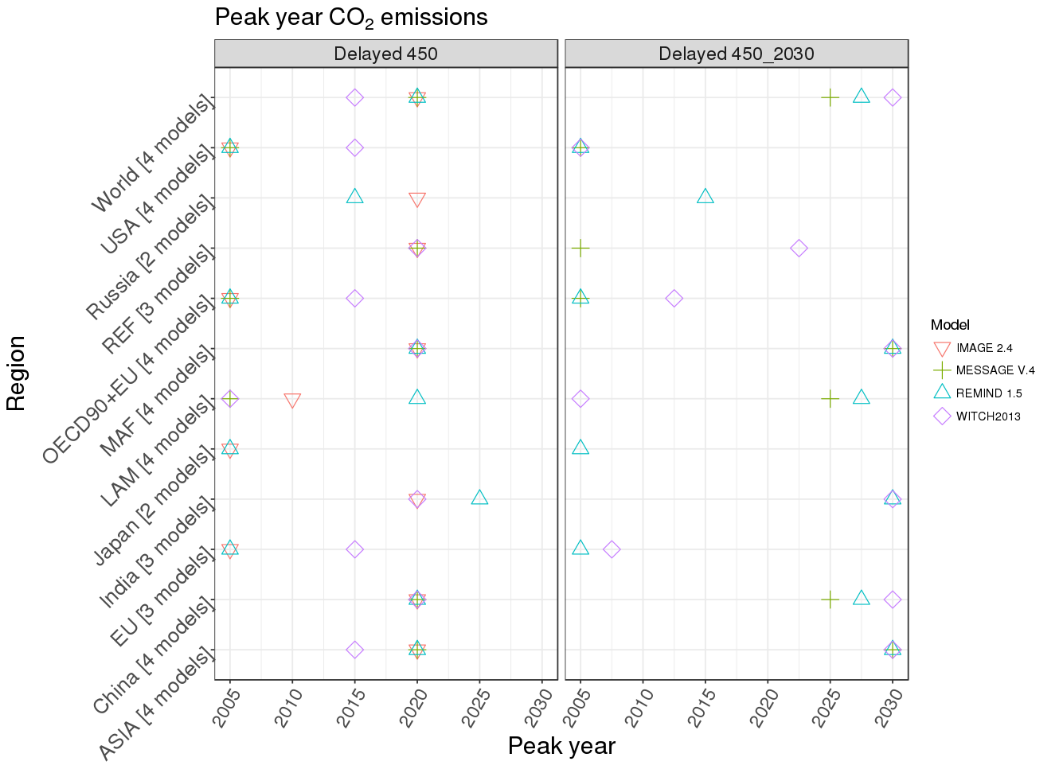


Upper figure: unharmonised model land use CO_2 emissions (blue), constant offset value (model data minus inventory data, green), and harmonised model land use CO_2 emissions (red, i.e. blue minus green). These harmonised land use CO_2 emissions are then added to the unharmonised greenhouse gas emissions excluding land use CO_2, to generate total greenhouse gas emission pathways including land use CO_2 (blue in the lower figure). Lower figure: total greenhouse gas emission pathways before (red) and after (blue) harmonisation.

Figure 10 shows peak years. Under the delayed mitigation 450 ppm CO_2eq scenario, all countries' greenhouse gas and CO_2 emissions are projected to peak no later than 2030, with OECD90 + EU, Latin America and Asia projected to peak earlier than reforming economies and the Middle East and Africa.

Figure 10. Regional peak years (when net emissions are at their maximum) for greenhouse gases (upper graph) and CO_2 (lower graph), in delayed mitigation 450 ppm CO_2eq scenarios (2020: left and 2030: right) of the LIMITS and AMPERE databases (Kriegler et al., 2014c; Riahi et al., 2015). For most OECD90 countries, the 450 ppm CO_2eq scenarios show a peak year in 2005, because the start year for model analysis was 2005. However, actual peak years may be earlier.





For models with multiple scenarios per category (delayed 2030), the mean was taken. Note that more models report CO_2 emissions than greenhouse gas emissions. Only results for regions covered by at least two models are shown.

Box 4. What are the regional and national emission reductions by 2030 and 2050 resulting from the greenhouse gas emission pathways that meet 2 °C?

Table 7 and Figure 11 present an overview of the projected greenhouse gas emission reductions (including and excluding LULUCF CO_2) for the four major economies (China, EU, India, and United States) by 2030 and 2050 for scenarios having a likely (>66%) chance of limiting global temperature increase to 2 °C during the 21st century. The net global greenhouse gas emissions projections for the world for the full technology cases of the delayed mitigation and cost-optimal 450 ppm CO_2eq scenarios from the AMPERE and LIMITS databases were used, in particular the median estimate over the various model studies with projections until 2100 (see Table 12 in Appendix III for reductions using the full set of models). More specifically: Delayed mitigation 450 ppm CO_2-eq pathways, i.e. limited action until 2020 and cost-optimal mitigation afterwards achieving the CO_2-equivalent concentration of 450 ppm by 2100.

Table 7: Projected regional greenhouse gas (including LULUCF CO_2) emissions by 2030 and 2050, relative to 2010, in delayed mitigation 450 ppm CO_2eq scenarios (negative numbers denote a reduction).

China	**2030**	**2050**
Delayed (2020)	**%**	**%**
Mean [min; max]	-10 [-22; 4]	-60 [-78; -45]
Median [10th percentile; 90th percentile]	**-12** [-20; 0]	**-59** [-75; -47]
Delayed (2030)	**%**	**%**
Mean [min; max]	37 [23; 54]	-57 [-64; -50]
Median [10th percentile; 90th percentile]	32 [25; 50]	-57 [-62; -51]

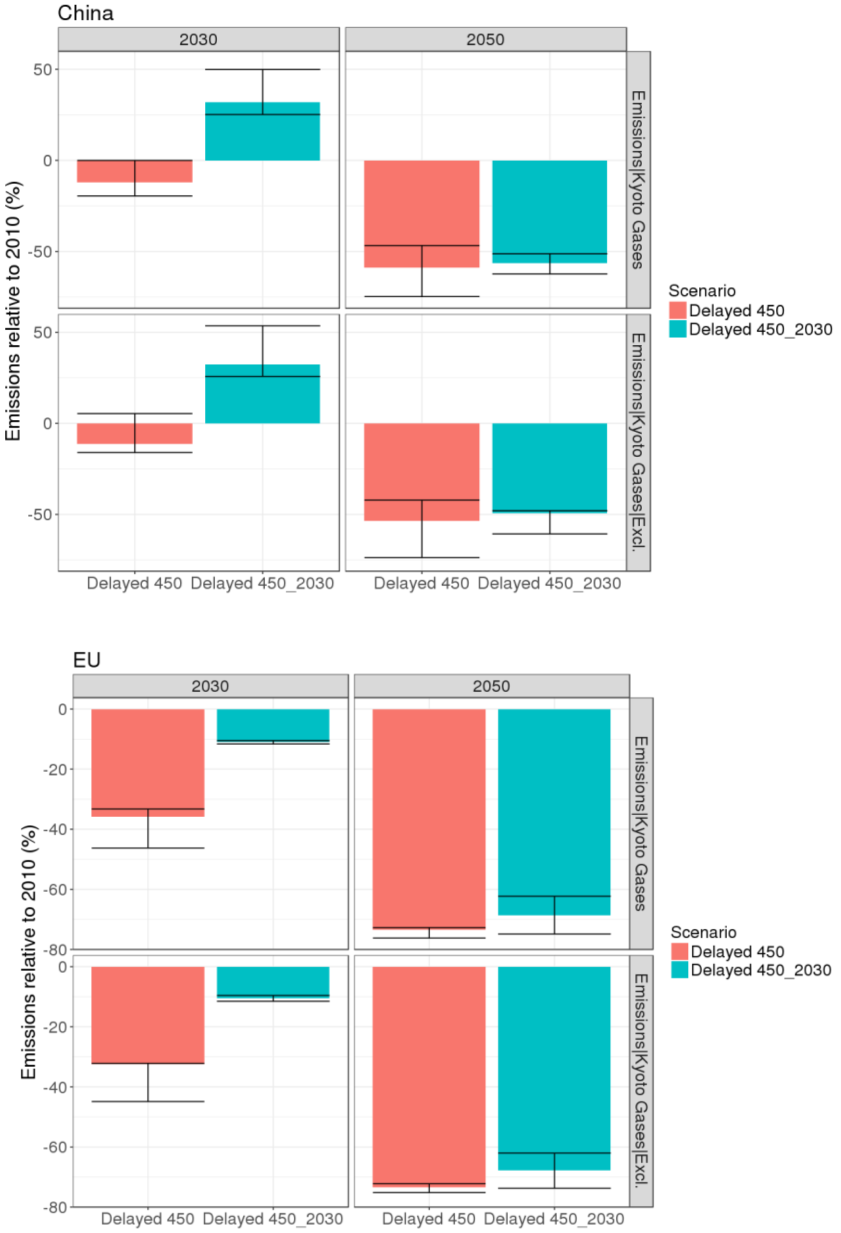
EU	**2030**	**2050**
Delayed (2020)	**%**	**%**
Mean [min; max]	-39 [-49; -33]	-74 [-77; -73]
Median [10th percentile; 90th percentile]	**-36** [-46; -33]	**-74** [-76; -73]
Delayed (2030)	**%**	**%**
Mean [min; max]	-11 [-12; -10]	-69 [-76; -61]
Median [10th percentile; 90th percentile]	-11 [-12; -11]	-69 [-75; -62]

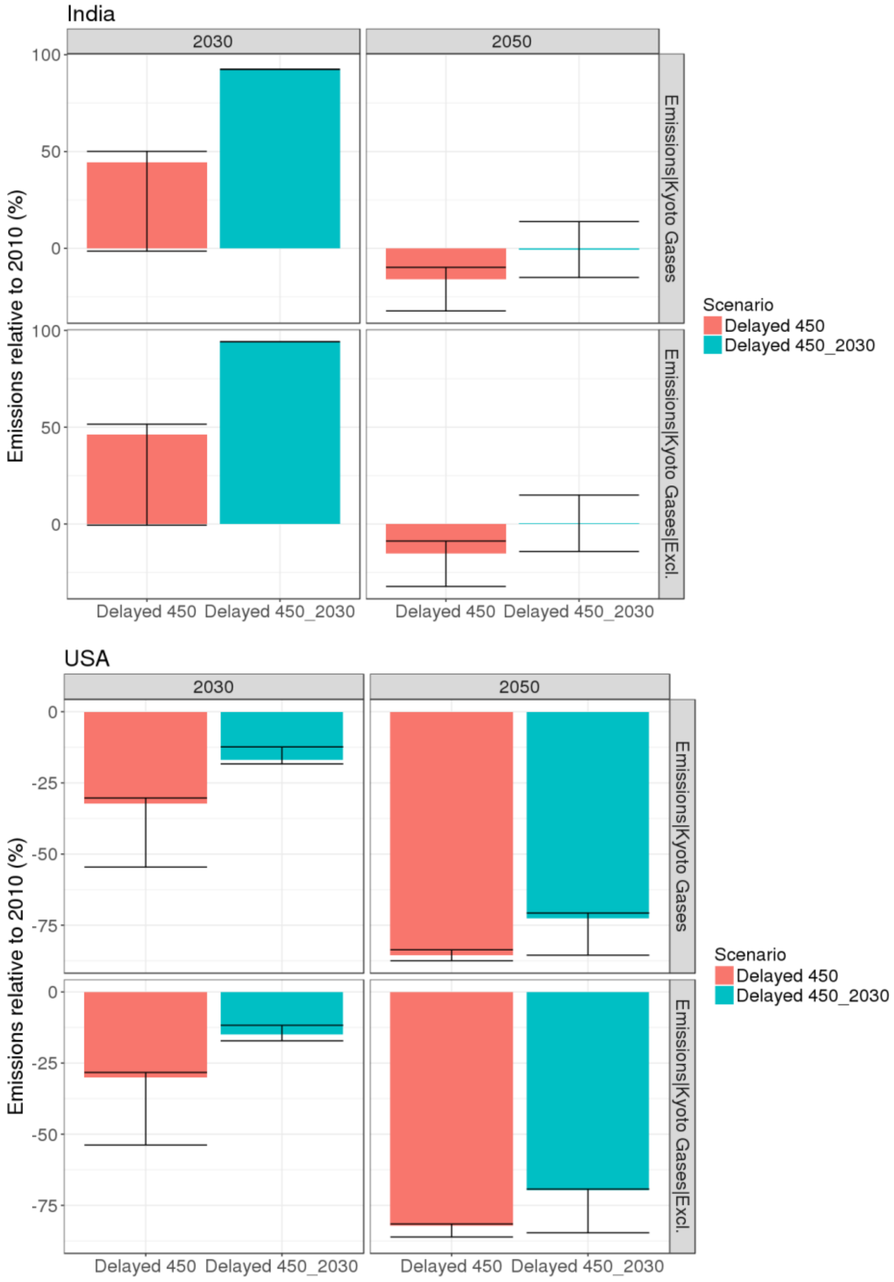
India	**2030**	**2050**
Delayed (2020)	**%**	**%**
Mean [min; max]	28 [-13; 51]	-20 [-36; -8]
Median [10th percentile; 90th percentile]	**45** [-1; 50]	**-16** [-32; -10]
Delayed (2030)	**%**	**%**
Mean [min; max]	92 [92; 93]	-1 [-19; 17]
Median [10th percentile; 90th percentile]	92 [92; 93]	-1 [-15; 14]

USA	**2030**	**2050**
Delayed (2020)	**%**	**%**
Mean [min; max]	-40 [-64; -30]	-86 [-88; -83]
Median [10th percentile; 90th percentile]	**-32** [-55; -30]	**-85** [-88; -84]
Delayed (2030)	**%**	**%**
Mean [min; max]	-16 [-19; -11]	-77 [-89; -70]
Median [10th percentile; 90th percentile]	-17 [-18; -12]	-73 [-86; -71]

Source: LIMITS and AMPERE databases (Kriegler et al., 2014c; Riahi et al., 2015)

Figure 11: Projected regional greenhouse gas emissions (upper: including LULUCF CO_2, lower: excluding LULUCF CO_2) by 2030 and 2050, relative to 2010, in delayed mitigation 450 ppm CO_2eq scenarios (left: 2020, right: 2030).





Negative numbers denote a reduction. Bar: median, error bar: 10th – 90th percentiles.
Source: LIMITS and AMPERE databases (Kriegler et al., 2014c; Riahi et al., 2015)*.*

3.4 What does greenhouse gas emissions neutrality mean, with respect to national CO_2 and non-CO_2 emissions?

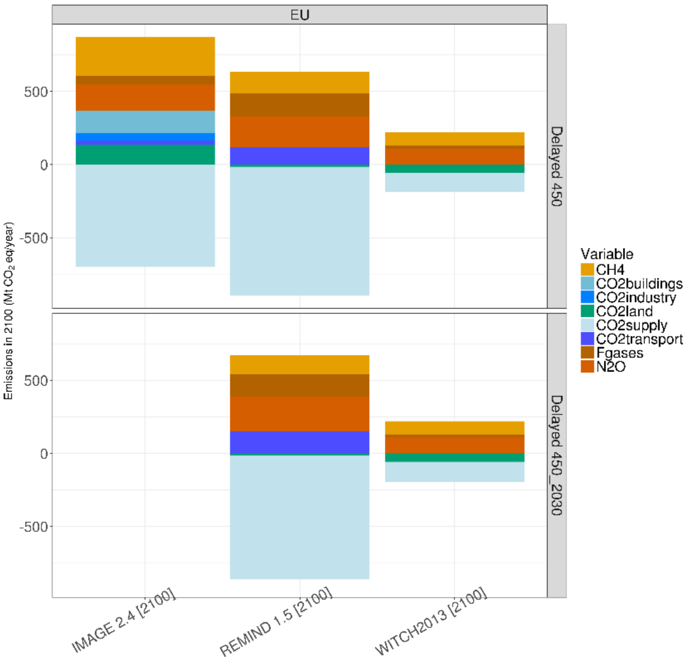
Countries with early phase-out generally have a relatively large potential for negative emissions and relatively low emission levels of both CO_2 (from the transport, industry and building sectors) and non-CO_2 greenhouse gases. Contrasting the OECD90+EU region to the Latin America region shows relatively larger remaining F-gas and transport CO_2 emissions in OECD countries, while Latin American countries show a relatively larger contribution from land use to negative emissions, albeit relatively large remaining CH_4 emissions due to agricultural production. High potential for negative emissions from reforestation and increased managed forest area is related to low land costs and high forest growth rates in Latin America.

Regional graphs of the emissions breakdown in the phase-out year are qualitatively similar to the global picture (Figure 5); therefore, we only show those regions that show some differences with the global picture (figures for other countries may be found in Appendix V). The EU (Figure 12) shows positive rather than negative CO_2 emissions from LULUCF, according to the IMAGE model.

Russia (reforming economies region) has relatively large potentials for negative emissions (1000 $MtCO_2eq$ in the phase-out year) and relatively small amounts of emissions from buildings and industry, contributing to early phase-out years for greenhouse gas emissions. China, part of the Asia region, Japan and the EU, part of the OECD90 + EU region, are also projected to have relatively large amounts of negative emissions in the phase-out year, but, at the same time, they have remaining non-CO_2 emissions as well as CO_2 emissions from transport, buildings and industry, contributing to their later phase-out for greenhouse gas emissions. Remaining emissions from transport, buildings, industry and non-CO_2 in India, part of the Asia region, are compensated for by negative emissions from energy supply and LULUCF. In the United States, part of the OECD90 and the EU region, negative emissions related to energy supply and LULUCF compensate mainly for the remaining non-CO_2 emissions and to a smaller extent also for CO_2 emissions from transport, buildings and industry.

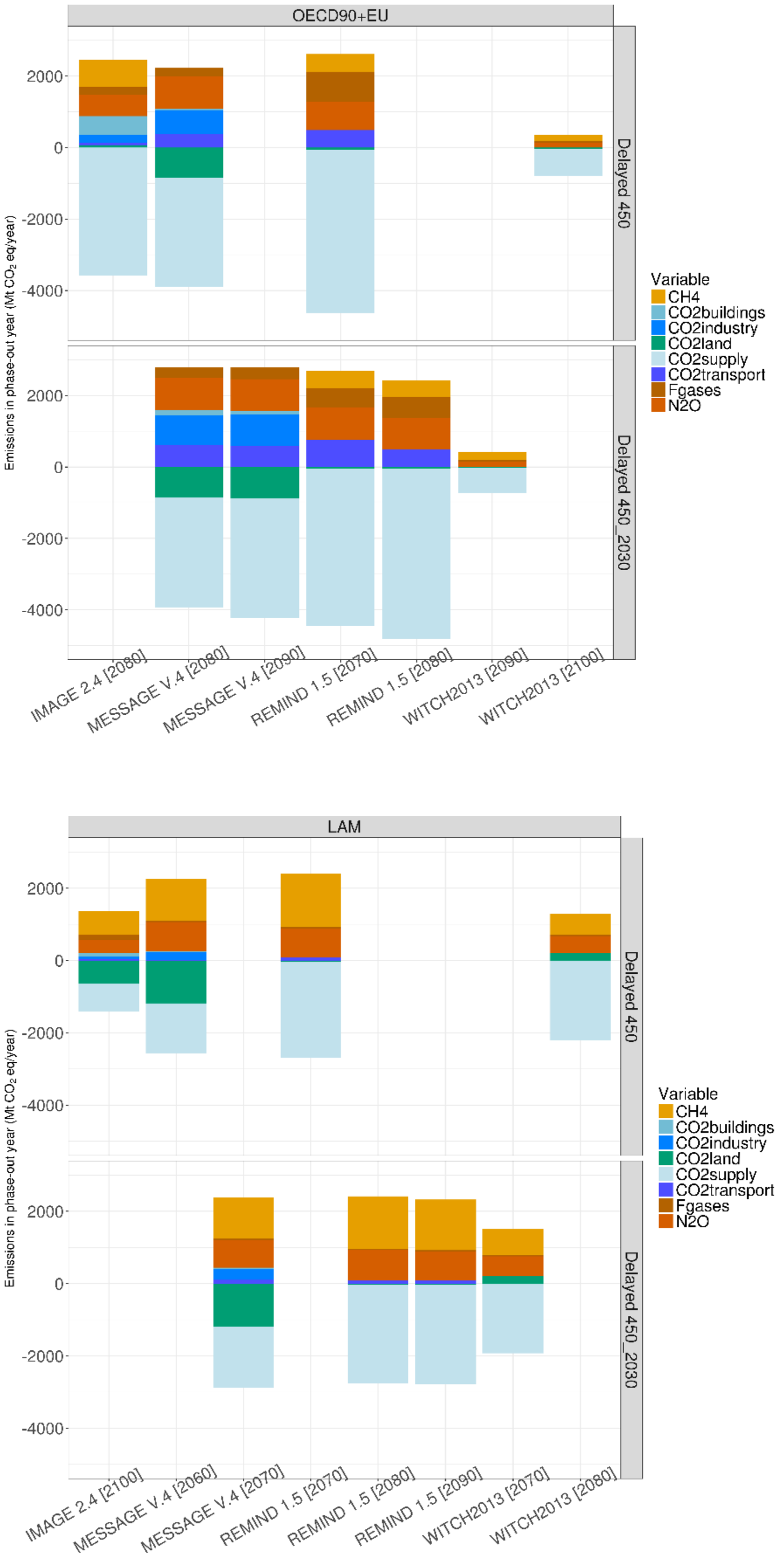
Contrasting the OECD90+EU region to the Latin America region (Figure 13) shows relatively larger remaining F-gas and transport CO_2 emissions in OECD countries, while Latin American countries show a relatively larger contribution from land use to negative emissions, albeit relatively large remaining CH_4 emissions due to agricultural production. High potential for negative emissions from reforestation and increased managed forest area is related to low land costs and high forest growth rates in Latin America. While Brazil uses productive lands to produce biomass and bioenergy, many times in combination with BECCS, much of the biomass is exported and so BECCS benefits may be accrued from other regions. This relates to the issue noted earlier, which requires further research: how are negative emissions achieved through BECCS allocated to regions?

Figure 12. Breakdown of emissions (MtCO$_2$eq) in the EU, in 2100, under delayed mitigation 450 ppm CO$_2$eq scenarios.



For models with multiple scenarios within a category (delayed 2030), the mean was taken. See Figure 5 for a further explanation of the categories. Source: PBL calculations are based on the LIMITS and AMPERE databases (Kriegler et al., 2014c; Riahi et al., 2015).

Figure 13: Breakdown of emissions (MtCO$_2$eq) in the OECD90+EU region (upper graph) and in the Latin America region (lower graph), in the phase-out year, under delayed mitigation 450 ppm CO$_2$eq scenarios.



For models with multiple scenarios within a category (delayed 2030), the mean was taken. See Figure 5 for a further explanation of the categories. Source: PBL calculations are based on the LIMITS and AMPERE databases (Kriegler et al., 2014c; Riahi et al., 2015).

3.5 When would global greenhouse gas emissions need to reach net zero, under 1.5 °C scenarios?

To limit global warming to 1.5 °C, emissions need to peak earlier and be reduced faster and deeper compared to 2 °C pathways. Global greenhouse gas emissions would need to reach net zero between 2050 and 2070, for a medium to likely chance of achieving the 1.5 °C target.

Scenarios that limit global warming to 1.5 °C are being developed at the time of writing, in preparation of the IPCC special report on 1.5 °C. Therefore, they will not be discussed extensively here, as the number of available scenarios is limited and findings are likely to change. A few observations can be made, though, based on a few early studies on the subject.

For limiting global warming to 1.5 °C, the story generally becomes one of 'peak earlier, reduce emissions faster and deeper'. For example, Rogelj et al. (2015a) found that the energy system transformations in 1.5 °C scenarios are similar to those in 2 °C scenarios, but show faster scale-up of mitigation, especially of CO_2, and deeper emission reductions by 2030 and 2050. Global carbon neutrality would need to be reached between 2045 and 2060 (Rogelj et al., 2015a). Schleussner et al. (2016) also show the difference between 1.5 and 2 °C pathways, with global CO_2 emissions reaching net zero around 2050 for 1.5 °C pathways and around 2060–2070 for 2 °C pathways. Total greenhouse gas emissions are projected to reach net zero around 2070 for 1.5 °C pathways and around 2080–2090 for 2 °C pathways. Robiou du Pont et al. (2017) show 1.5 °C pathways that reach net zero greenhouse gas emissions around 2075 (2059–2087). These scenarios reach, on average, 32.6 $GtCO_2eq$ by 2030, which is lower than 2030 emission levels presented by Rogelj et al. (2015a) and UNEP (2016), approximately 39 $GtCO_2eq$. Other new scenarios, developed in the ADVANCE project (Luderer et al., 2016), show even lower emission levels by 2030 (approximately 25 $GtCO_2eq$). They further show net zero emissions by 2050, which is 20 years earlier than in the above studies. These differences can be explained by different 2010 emission levels and a higher likelihood to achieve the target assumed in ADVANCE (66%, versus 50% in the UNEP emissions gap report), but also because these scenarios have to take drastic measures to reach the target, given that they incorporate more recent international pledges. A key finding of the ADVANCE study was further that most of the additional emission reductions in 1.5 °C scenarios compared to 2 °C scenarios came from the demand side (efficiency improvements and electrification). In addition, negative emissions are required: cumulatively, 500 $GtCO_2$ during this century (Luderer et al., 2016). Most recently, Rogelj et al. (2018) presented 1.5 °C (1.9 W/m^2) scenarios under SSP assumptions, based on a set of scenarios from six Integrated Assessment Models. In these scenarios, greenhouse gas emissions are projected to peak before 2030, decline rapidly in the following decades, and reach net zero around 2055 – 2075. CO_2 emissions are projected to reach net zero earlier. The timing of neutrality depends on short-term action: scenarios with 2030 emissions above 40 Gt CO_2eq per year are projected to reach net zero greenhouse gas emissions before 2060. These scenarios see a rapid change from fossil fuels to low-carbon energy supply, reduced energy use and carbon dioxide removal (CDR). As the latter is debated (e.g. due to concerns about feasibility or the effect on land use), Van Vuuren et al. (2018) developed alternative deep mitigation pathways: scenarios with measures such as lifestyle change, additional non-CO_2 greenhouse gas emission reduction, and more rapid electrification of energy demand. These measures reduce, but not completely eliminate, the need for CDR. Kriegler et al. (2018) also analysed the need for CDR in 1.5 °C scenarios, identifying the conditions for 1.5 °C pathways with limited CDR deployment or without temporary overshoot of the temperature target. These include final energy demand reduction, electrification of energy end uses, and decarbonisation of energy supply. Carbon neutrality is reached before 2050 in the 1.5 °C pathways.

3.6 What would the emission pathways be, when based on effort sharing instead of cost-optimisation?

Future emission reduction targets based on effort-sharing approaches that account for equity principles are often largely determined by the way the equity principle is implemented. In addition, the distribution of emission reduction targets may also differ significantly between such approaches. This may lead to a wide range of outcomes, which can be implemented by countries domestically, through emissions trading, or financial transfers. For achieving the 2 °C target, the 2030 emission target levels under all effort-sharing approaches would need to be approximately half of the 2010 emission levels in OECD1990 countries (with a wide range), roughly two-thirds of the 2010 level in the Economies in Transition (EIT), roughly be around or slightly below the 2010 level in Asia, slightly above the 2010 level in the Middle East and Africa, and well below the 2010 level in Latin America.

Several studies have analysed future greenhouse gas emissions allowances and reduction targets for different regions based on a wide range of effort-sharing approaches that account for equity principles (for an overview, see Höhne et al., 2014). The IPCC AR5 report (Clarke et al., 2014) grouped the existing effort-sharing approaches into six categories using specific definitions of equity principles and distributive justice, including *responsibility, capability, equality, responsibility-capability-need, equal cumulative per capita emissions and staged approaches*, based on Höhne et al. (2014). The principle of cost-effectiveness, which is modelled by applying a uniform carbon tax across all countries, is often used as a reference to compare approaches in the six categories with.[12] Some approaches may lead to extreme outcomes, which might be impossible to achieve by domestic emission reductions. This can be overcome by allowing emissions trading between countries.

The previous sections in this chapter presented regional emission pathways that were all based on this cost-effective approach of allocating the reductions across countries. The main focus of this section is to present initial allocations of emission reduction targets from a wide range of effort-sharing approaches based on the IPCC AR5 effort sharing categories, for reaching the climate goals of 2 °C and 1.5 °C of the Paris Agreement, without an assessment of the feasibility and costs of these approaches. As the results are based on literature, they are not necessarily consistent with the neutrality analyses presented in section 3.3, but are included as an indication of possible different allocations.

Höhne et al. (2014) assessed more than 40 studies and concluded that the reduction targets resulting from the effort-sharing approaches are often largely determined by the way the equity principle is implemented. They further found that the distribution of emission reduction targets can differ significantly among such approaches, depending on the effort sharing approach used, the concentration stabilisation level and shape of the global emissions pathway. Höhne et al. (2014) also presented reduction targets at the level of the IPCC AR5 regions, and concluded that for stabilising greenhouse gas concentrations at 450 ppm CO_2eq (likely chance of achieving the 2 °C objective), the 2030 allowances under all effort sharing approaches would be approximately half of the 2010 emissions in OECD1990 (with a large range), roughly two-thirds in the Economies in Transition (EIT), roughly at the 2010 emissions level or slightly below in Asia, slightly above the 2010 level in the Middle

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[12] The initial allocation based on effort sharing and a cost-effective distribution is usually not the same for most countries. Studies then assume that emissions allowances are traded or that financial transfers occur, so that reduction targets are achieved, emissions are sufficiently reduced globally, and costs are minimized, all at the same time (e.g. den Elzen et al., 2008; Hof et al., 2016).

East and Africa, and well below the 2010 level in Latin America. No robust conclusions were presented for achieving the 1.5 °C objective.

The study by Robiou du Pont et al. (2017) is one of the few studies that presented countries' reduction targets for 2030 and 2050 for a wide range of effort-sharing approaches for achieving the 2 °C and 1.5 °C objectives. It also presented the timing of net zero greenhouse gas emission allowances. More specifically, Robiou du Pont et al. (2017) identified global cost-optimal mitigation scenarios consistent with the Paris Agreement goals and allocated their emissions dynamically to countries according to five equity approaches, each representing one of the IPCC AR5 equity categories. Robiou du Pont et al. (2017) did not apply the responsibility category, and used the grandfathering approach for the *Staged* category, which is based on an allocation of constant emissions ratios for all countries, and does not assume increasing participation of countries that take on higher commitments.

Table 8. Summary of timing of reaching net zero greenhouse gas emission targets, and emission reduction targets by 2030 and 2050 for selected countries, for 2 °C and 1.5 °C pathways. Averages and ranges over the five emission allocation approaches are presented.

Country/ Region	**Climate goal**	**Net zero year**	**% change in net GHG emissions relative to 2010 levels**	
		All GHG	**2030**	**2050**
World	2 °C	2082	-5	-47
	1.5 °C	2075	-3	-78
Brazil	2 °C	2084 (2076 to 2100)	-5 (-35 to 19)	-54 (-74 to -30)
	1.5 °C	2078 (2068 to 2100)	-36 (-28 to -54)	-78 (-89 to -64)
China	2 °C	2075 (2057 to 2083)	-27 (-59 to 6)	-70 (-95 to -44)
	1.5 °C	2075 (2048 to 2075)	-48 (-71 to -19)	-88 (-102 to -76)
EU28	2 °C	2068 (2044 to 2083)	-38 (-62 to -5)	-86 (-122 to -47)
	1.5 °C	2057 (2034 to 2075)	-62 (-84 to -33)	-106 (-149 to -78)
India	2 °C	2087 (2082 to 2100)	72 (-5 to 155)	40 (-47 to 152)
	1.5 °C	2081 (2073 to 2100)	30 (-33 to 102)	-24 (-78 to 63)
Japan	2 °C	2067 (2038 to 2083)	-46 (-72 to -5)	-91 (-138 to -47)
	1.5 °C	2056 (2029 to 2075)	-67 (-104 to -33)	-109 (-156 to -78)
Russia	2 °C	2074 (2051 to 2083)	-39 (-62 to -5)	-76 (-99 to -47)
	1.5 °C	2065 (2042 to 2075)	-57 (-73 to -33)	-96 (-29 to -78)
United States	2 °C	2067 (2045 to 2083)	-44 (-66 to -5)	-89 (-119 to -47)
	1.5 °C	2057 (2036 to 2075)	-64 (-80 to -33)	-109 (-144 to -78)

Source: Robiou du Pont et al. (2017).

4. What are the options for negative emissions?

4.1 Overview

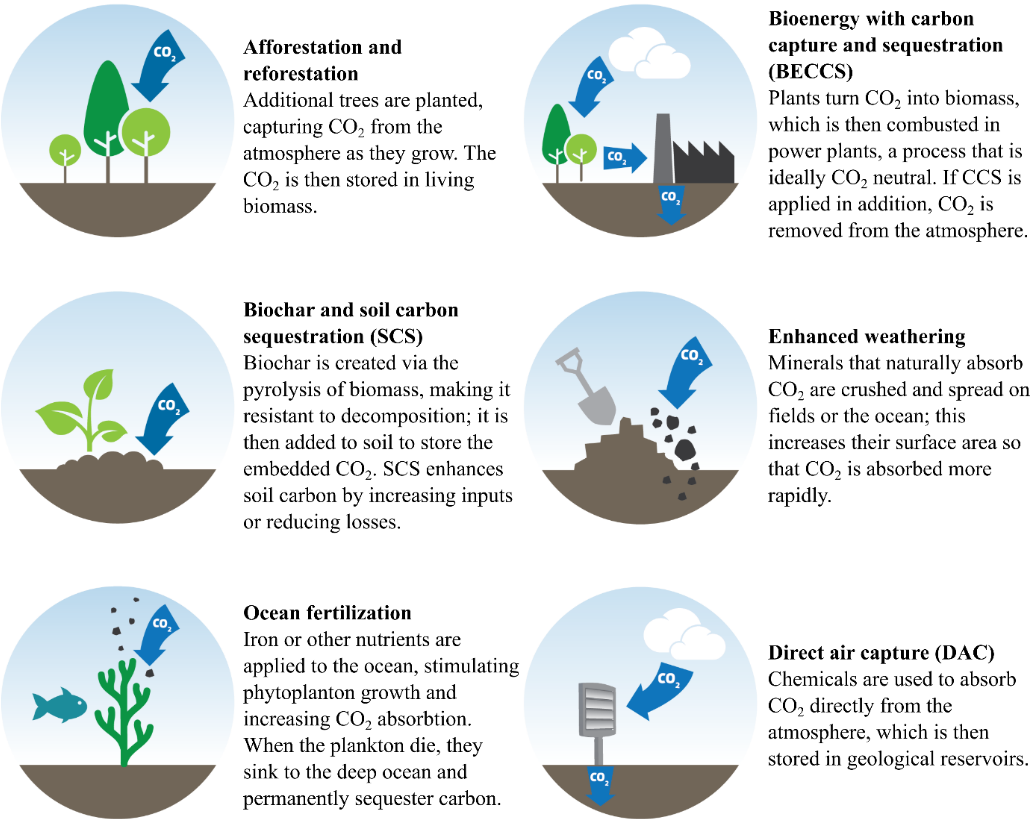
There is a range of options to generate negative emissions, each with their own advantages and drawbacks. Most options are either land-based or energy system measures. Bioenergy, combined with carbon capture and storage (BECCS), is the major negative emissions technology included in integrated assessment models, leading to projected carbon storage of 10 to 20 GtCO$_2$ per year, in the second half of the century.

Carbon Brief (2016) identified the following options for negative emissions (see reference for more information including pros and cons of each option):

- *'Afforestation and reforestation: Planting trees where there were previously none (afforestation) or restoring areas where the trees have been cut down or degraded (reforestation).*
- *Biochar: Burning biomass to create biochar and adding it to soils where it holds on to its carbon for hundreds or thousands of years.*
- *BECCS: Farming bioenergy crops, which extract CO$_2$ from the atmosphere as they grow, and then burning them for energy and sequestering the resulting emissions underground.*
- *'Blue carbon' habitat restoration: Conservation and restoration of degraded coastal and marine habitats, such as salt marshes, mangroves, and seagrass beds, so they continue to draw CO$_2$ out of the air.*
- *Building with biomass: Using plant-based materials in construction, storing carbon and preserving it for as long as the building remains standing.*
- *Cloud or ocean treatment with alkali: Adding alkali to clouds or the ocean to enhance the reaction that sees CO$_2$ dissolve in water, removing it from the air.*
- *Direct air capture: Sucking carbon dioxide out of the air and either burying it underground or using it in chemical processes to make anything from plastic to fuel.*
- *Enhanced ocean productivity: Adding iron or nitrogen to the ocean to increase the rate at which tiny microscopic plants photosynthesise, thus accelerating their take up of atmospheric CO$_2$.*
- *Enhanced weathering: Spreading pulverised rocks onto soils and/or the ocean to ramp up the natural rock weathering process that takes up CO$_2$ from the atmosphere and eventually sees it washed into the ocean as bicarbonate.*
- *Soil carbon sequestration: Using measures, such as modern farming methods, grassland restoration and creation of wetlands and ponds, to reverse past losses of soil carbon and sequester CO$_2$.'*

Minx et al. (2017) generated an overview of the literature on negative emissions technologies (NETs) using scientometric methods and topic modelling. They found that the literature on NETs has started later than the literature on climate change, but is currently developing more quickly. However, the literature on NETs still only accounts for 1% of the most recent climate change literature (2015). According to their classification (Minx et al., 2017), discussion on NETs takes place in three different thematic clusters: energy systems, forestry, and other land-based measures (e.g. biochar and other soil carbon options). The focus in long-term mitigation scenarios has mostly been on BECCS, although recently, other NET options have been evaluated as well (Chen and Tavoni, 2013; Fuss et al., 2013; House et al., 2011; Humpenöder et al., 2014; Kreidenweis et al., 2016; Wise et al., 2009).

Figure 14. Options for negative emissions.



Afforestation and reforestation
Additional trees are planted, capturing CO_2 from the atmosphere as they grow. The CO_2 is then stored in living biomass.

Bioenergy with carbon capture and sequestration (BECCS)
Plants turn CO_2 into biomass, which is then combusted in power plants, a process that is ideally CO_2 neutral. If CCS is applied in addition, CO_2 is removed from the atmosphere.

Biochar and soil carbon sequestration (SCS)
Biochar is created via the pyrolysis of biomass, making it resistant to decomposition; it is then added to soil to store the embedded CO_2. SCS enhances soil carbon by increasing inputs or reducing losses.

Enhanced weathering
Minerals that naturally absorb CO_2 are crushed and spread on fields or the ocean; this increases their surface area so that CO_2 is absorbed more rapidly.

Ocean fertilization
Iron or other nutrients are applied to the ocean, stimulating phytoplanton growth and increasing CO_2 absorbtion. When the plankton die, they sink to the deep ocean and permanently sequester carbon.

Direct air capture (DAC)
Chemicals are used to absorb CO_2 directly from the atmosphere, which is then stored in geological reservoirs.

Source: Minx et al. (2017)

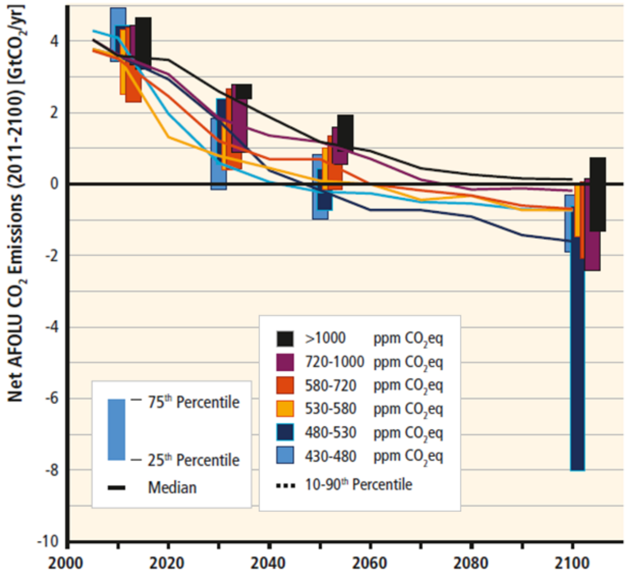
Although negative emissions technologies are widely used in 2 °C scenarios from IAMs, there are limits to and costs related with their applicability (Smith et al., 2016). These relate to the use of land, water, nutrients, energy, and impacts on albedo. For options using CCS (e.g. DAC and BECCS), geological storage capacity could be limiting. For DAC additionally, its costs and energy use are currently limiting (Smith et al., 2016). For enhanced weathering, e.g. using olivine, large areas of land would be required, while the potential for carbon removal is lower than that of other negative emissions options. Afforestation and reforestation (see more in Section 3.2 and Chapter 4) may have unintended consequences such as decreased albedo and increased evapotranspiration, but are relatively cheap. Competition for land could be an issue for this option as well as for BECCS. Other barriers for BECCS could be nutrient demand and water use (Smith et al., 2016).

4.2 Afforestation and reforestation

Afforestation and reforestation are commonly defined as direct human-induced conversion of non-forest to forest land through planting, seeding, and/or the human-induced promotion of natural seed sources. The two terms can be distinguished by how long the non-forest condition has prevailed. Afforestation and reforestation are commonly used options within IAMs to reach negative CO_2 emissions; however, the range between estimates is commonly high. Benítez et al. (2007) project that at a price of 13.6 USD/tCO_2, the annual sequestration from afforestation and reforestation for the first 20 years could amount to 0.5 $GtCO_2$ per year on average. For the first 40 years, the average annual sequestration was estimated to be 0.8 $GtCO_2$ per year. Starting from a carbon price of 5 USD/tCO_2, Sathaye et al. (2006) have estimated that afforestation could on average contribute with 0.5 $GtCO_2$ per year from 2010 to 2050, and 1.3 $GtCO_2$ per year from 2010 to 2100. Strengers et al. (2008) reported a mitigation potential from afforestation of up to 2.7 $GtCO_2$ per year by the end of the twenty-first century under the most optimistic assumptions, but indicated that around 1.2 $GtCO_2$ per year would be a more realistic figure. In pessimistic cases, however, expansion of the area under agriculture implies that there would be no realistic potential.

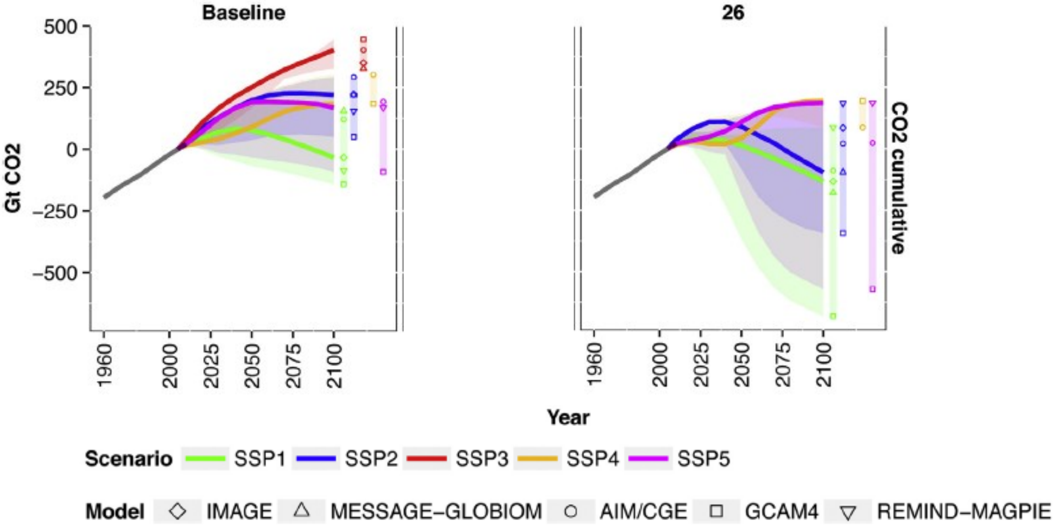
In terms of IAM scenarios and the scenarios assessed in the AR5 (see Figure 15), most scenarios show declining CO_2 emissions from land use as a result of declining deforestation rates and a net uptake of CO_2 as a result of reforestation after 2050. However, the range between estimates is commonly high which is illustrated by the wide range of outcomes for the contribution of land-use-related CO_2 emissions in the scenarios assessed within the AR5. A similar development of the land-use emissions and removals was shown by Popp et al. (2017) for the SSP scenarios (see Figure 16). The SSP scenarios expect that annual CO_2 emissions would decrease steadily until the end of the century in a baseline development. Also, in a mitigation case (RCP2.6), the SSP scenarios expect that afforestation would increase terrestrial carbon sequestration, leading to a net uptake of CO_2. As of 2100, the land-use sector is expected to sequester 3.3 $GtCO_2$ per year in SSP1 (IMAGE), 3.7 $GtCO_2$ per year in SSP2 (MESSAGE-GLOBIOM), and close to zero in SSP4 (GCAM) and SSP5 (REMIND-MAGPIE).

Figure 15. Net CO_2 emissions from land use as a function over time in mitigation scenarios.



Source: Clarke et al. (2014) (p. 436).

Figure 16. Change in global cumulative land-use change emissions since 2005 of the five SSP marker scenarios for the baseline (left column), and RCP-2.6 (right column) cases.



Coloured lines indicate the marker model results for each SSP. Coloured bars indicate the range of data for 2100, across all marker and non-marker projections, for each SSP. The grey line shows historical trends based on RCP data. Source: Popp et al. (2017).

4.3 Bioenergy

Globally, the use of negative emissions in the IPCC AR5 scenarios ranges from 0 to approximately 350 $GtCO_2$ cumulatively over the second half of the century. These can be realised by, mostly, afforestation and bioenergy with CCS. The SSPs assume a phase-out of traditional biofuel use, but apply modern biofuels with varying assumptions on their potential (Van Vuuren et al., 2017). Global biomass use in primary energy under the RCP-2.6 scenarios (across SSP1–5) ranges from approximately 60 to 200 EJ/year by 2050, with BECCS projected to store up to 8 $GtCO_2$ by 2050 (Riahi et al., 2017; Van Vuuren et al., 2017) (see Table 9). Smith et al. (2016) cite modelling exercises showing BECCS deployment in 2 °C scenarios of around 3.3 GtC/year (i.e. ~12 $GtCO_2$). However, the feasibility of such large-scale deployment of BECCS is being questioned (e.g. Anderson and Peters, 2016; Tollefson, 2015), and often there are calls for research into the implications of BECCS and for a debate on the potential and risks (Geden and Schäfer, 2016). Smith et al. (2016) did such a study, quantifying the potential impacts of various negative emissions technologies on land use, water, nutrients, albedo, energy use, and greenhouse gas emissions. CO_2 storage is assumed to be even larger under 1.5 °C scenarios (Table 9).

Table 9. Projected biomass use, agricultural demand for bioenergy and CO_2 storage by BECCS in SSP1–5 RCP-2.6 scenarios (Riahi et al., 2017), for 2050 and 2100 (minimum – maximum over all scenarios with a radiative forcing level of 2.6 W/m^2)

	2050	**2100**
Biomass use *(EJ/year)*	60 – 200	Up to 475
Biomass with CCS	0 – 160	Up to 420
Biomass without CCS	20 – 180	Up to 350
Energy crops *(EJ/year)*	0 – 130	Up to 400
Agricultural demand for bioenergy *(Million tonnes dry matter per year)*	480 – 9350	2290 – 23382
CO_2 storage by BECCS *($GtCO_2$ per year)*	0.17 – 8	2 - 21

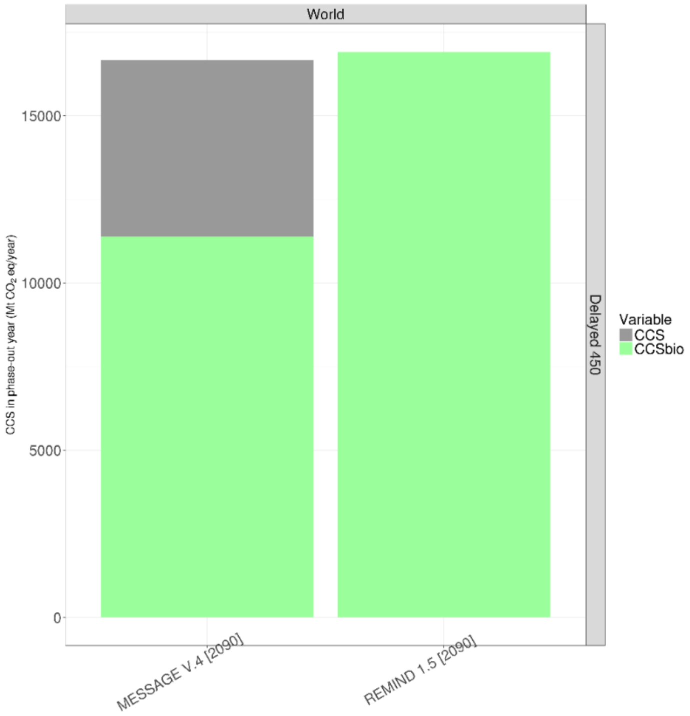
Table 10. Cumulative CO_2 storage in 1.5 °C and 2 °C scenarios. Source: Schaeffer et al. (2015)

	Until 2050 ($GtCO_2$)	**Until 2100 ($GtCO_2$)**
Total cumulative CO_2 storage		
Returning warming to below 1.5 °C by 2100 with 50% chance	135 (100–235)	790 (420–1070)
Holding warming to below 2 °C during the 21st century with 66% chance	105 (75–170)	790 (555–990)
Cumulative storage for CO_2 from biomass energy		
Returning warming to below 1.5 °C by 2100 with 50% chance	45 (5–165)	520 (155–955)
Holding warming to below 2 °C during the 21st century with 66% chance	22 (5–75)	440 (155–780)

Additional analysis – LIMITS and AMPERE

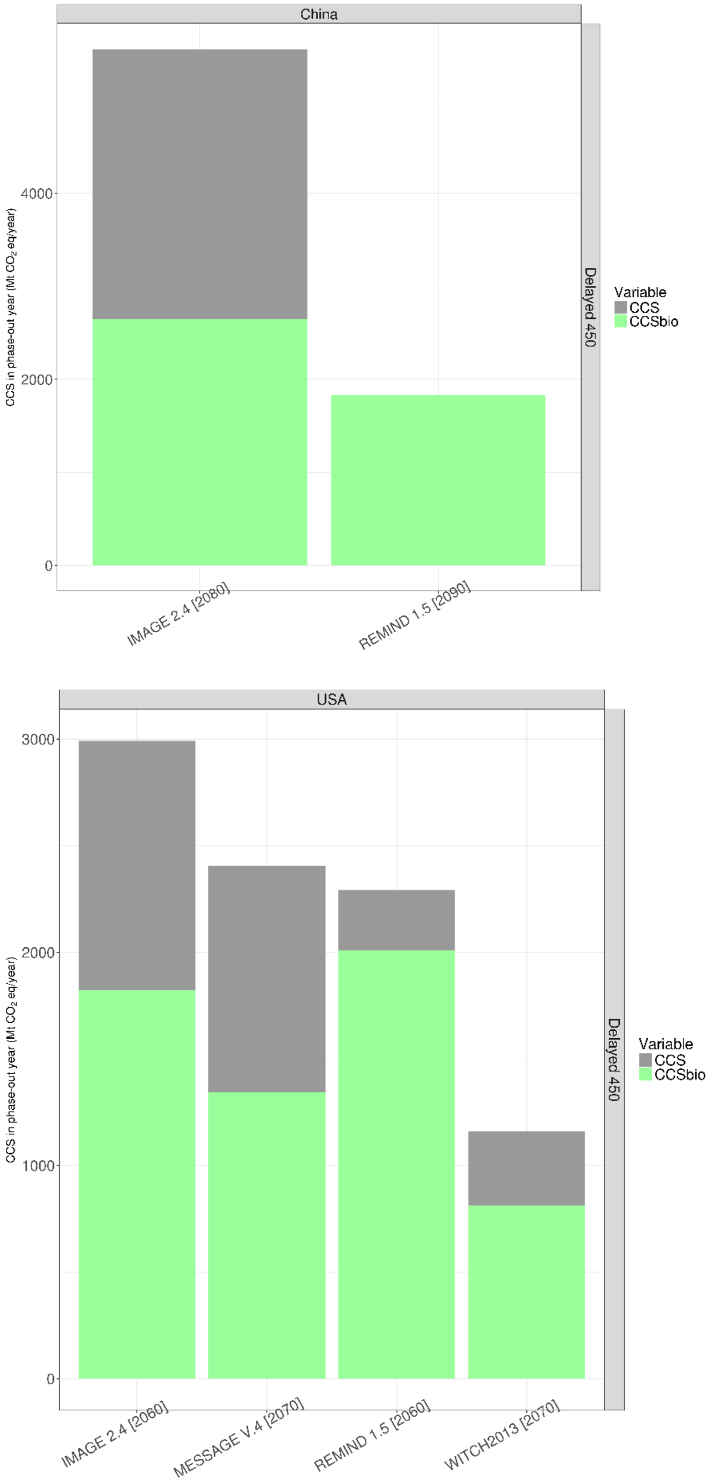
In delayed mitigation 450 ppm CO_2eq scenarios, storage of CO_2, using CCS, is projected to range from 0 to 6 GtCO_2 globally, while CCS in combination with biomass is projected to store 12 to 17 GtCO_2 in the phase-out year for greenhouse gas emissions (Figure 17), well within the SSP range in the 2.6 W/m^2 scenarios. Regionally, these numbers may differ, but IAMs project deployment of both CCS and BECCS in many countries, with China and the United States both storing 1 to 4 GtCO_2 (Figure 18).

Figure 17. Globally stored amounts of CO_2 in the phase-out year, in delayed mitigation 450 ppm CO_2eq scenarios (excluding IMAGE and WITCH, as they do not project a phase-out year for global greenhouse gas emissions)



CCS means 'total carbon dioxide emissions captured and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers'. 'CCSbio' means 'total carbon dioxide emissions captured from bioenergy use and stored in geological deposits'. 'CCS' does not include 'CCSbio' to avoid double counting (i.e. CCS shown here was calculated as total reported CCS minus 'CCSbio'). Source: PBL calculations are based on the LIMITS and AMPERE databases (Kriegler et al., 2014c; Riahi et al., 2015).

Figure 18. Regionally stored amounts of CO_2 in the phase-out year, in delayed mitigation 450 ppm CO_2eq scenarios (China and United States are shown as examples with relatively large amounts of negative emissions)



CCS means 'total carbon dioxide emissions captured and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers'. 'CCSbio' means 'total carbon dioxide emissions captured from bioenergy use and stored in geological deposits'. 'CCS' does not include 'CCSbio' to avoid double counting (i.e. CCS shown here was calculated as total reported CCS minus 'CCSbio'). Source: PBL calculations are based on the LIMITS and AMPERE databases (Kriegler et al., 2014c; Riahi et al., 2015).

4.4 Microalgae production

Intensive development of microalgae could be exploited as a source for animal feedstock, thereby freeing up land for forest plantations and providing emissions mitigation from the energy and LULUC sectors of up to 544 ± 107 GtC by 2100.

Walsh et al. (2015) studied the potential development and use of microalgae as an energy source, feedstock for livestock and potential land-sparing consequences of its development. The authors argue that intensive development of microalgae can be exploited as a source of animal feedstock, offsetting anticipated growth in demand for meat and dairy while allowing vast areas of agricultural land to be repurposed for biomass production or habitat restoration. Overall, the authors argue that microalgae and its use as a feedstock can free up to 2 billion hectares of land currently used for pasture and feed crops. Forest plantations established on these areas can conceivably meet 50% of global primary energy demand, resulting in emissions mitigation from the energy and LULUC sectors of up to 544 ± 107 GtC by 2100.

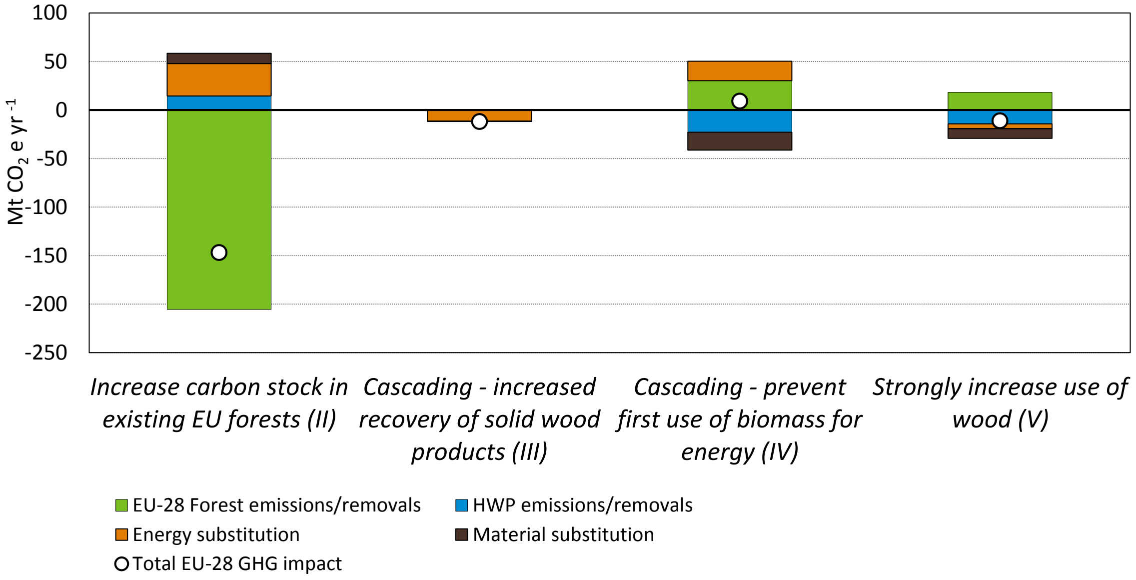
4.5 Storing carbon in woody products

Studies assessing the potential climate benefits of wood use show that forest harvest reduction scenarios have the largest short term (2030) climate benefits, while scenarios increasing consumption of long-lived woody products (i.e. construction sector) have the largest long term (2100) climate benefit.

Few studies have assessed and quantified the potential climate benefits of increased consumption of woody products to substitute carbon intensive materials (material substitution) on a national or global level. One assessment by Rüter et al. (2016) analyses the combined effect of policy scenarios on the following carbon pools: carbon sequestration and storage in EU forests, carbon storage in harvested wood products in the EU, substitution of wood products for functionally equivalent materials and substitution of wood for other sources of energy, and displacement of emissions from forests outside the EU. The study focuses on the EU28 and analyses consequences of the policy scenarios, in terms of total greenhouse gas effect. The study finds that a scenario with a strong increase in the material use of wood (especially the construction sector) can reduce greenhouse gas emissions by using alternative materials, compared to the *ClimWood2030 reference* scenario, by 11 Mt CO_2eq yr^{-1} on average (see scenario 'Strongly increase use of wood (V) ' in Figure 19 below).

It is important to note that the authors only assess the climate benefits for the period of 2000 until 2030. Studies on a national level for example for Switzerland and Sweden have shown that scenarios having the strongest short-term mitigation effect (i.e. 2030) can be the opposite of the scenario having the strongest long-term mitigation potential (i.e. 2100) (Taverna et al., 2007; Lundmark et al., 2014). Both of these studied showed that in the short term, the scenario with the largest mitigation potential is that of reducing harvest and increasing carbon stocks in forest. However, in the long term, the studies showed that the scenario with the largest mitigation potential is that of increased consumption of long-lived woody products.

Figure 19. Average annual impact under scenarios for EU-28 parameters on greenhouse gas balances, as compared to the ClimWood2030 reference scenario, 2021–2030 period, detailed per contributor [in Mt CO_2eq/year].



Source: Rüter et al. (2016)

5. Land-use implications of achieving greenhouse gas emissions neutrality

5.1 What are the land-use implications of 2 °C scenarios?

The implications of the Shared Socio-Economic Pathways (SSPs) and Representative Concentration Pathways (RCPs) for possible land-use change and consequences for the agricultural system, food provision and prices as well as greenhouse gas emissions were assessed by Popp et al. (2017). For the assessment, five IAMs with distinctive land-use modules were used for the translation of the SSP narratives into quantitative projections. The five models that were included in the assessment were IMAGE (for more details, see Doelman et al., 2018), MESSAGE-GLOBIOM, AIM/CGE, GCAM4, and REMIND-MAGPIE. This chapter assesses the implications of scenarios with a likely (>66%) chance of limiting global temperature to below 2 °C, and focuses on the SSP2 RCP-2.6 scenario (hereafter referred to as *2 °C scenarios)*. The SSP2 RCP-Baseline scenario represents a baseline scenario development without climate change mitigation efforts (hereafter referred to as a *baseline scenario)*, for which greenhouse gas concentrations are projected to stabilise at 785 ppm CO_2eq (Fricko et al., 2017). Further information concerning the outcomes of other scenarios can be found in Popp et al. (2017).

(a) What are the general land-use implications related to 2 °C scenarios?

According to integrated assessment models (IAMs) (i.e. IMAGE, MESSAGE-GLOBIOM, AIM/CGE, GCAM4, REMIND-MAGPIE), the dynamics of agricultural land are expected to be affected by land-demanding mitigation options, such as afforestation, avoided deforestation, improved agricultural management and bioenergy crop production.

Under a *baseline scenario*, population dynamics, per capita caloric consumption and animal calorie shares increase, moderately (Popp et al., 2017). As a consequence, global demand for crops (plus 2860 million tonnes dry matter by 2100, about 76% increase from 2005 levels) and livestock products (plus 235 million tonnes dry matter by 2100, about 94% increase from 2005 levels) increases, moderately, under the scenario with the largest shares and increases in demand, over time, in most Asian countries with the exception of the Middle

East, Japan and the former Soviet Union states (ASIA). Cropland use, for food and feed production, generally increases, moderately, in the IAMs (average increase of 183 million ha, between 2010 and 2100) (see Figure 20). This is due to relatively high demand, combined with high yield increases (by a factor of 1.6, between 2005 and 2100). Agricultural expansion mainly occurs in the Middle East and Africa (MAF) as well as in Latin America and the Caribbean (LAM), as a result of medium demand for livestock products that will be met mostly through rather extensive livestock production systems. This agricultural land expansion mainly occurs at the expense of forests (LAM) and other natural areas (MAF). The IAMs all expect that the global forest area will decrease, over time (average decrease of 147 million ha, between 2010 and 2100), and that a moderate amount of land will be set aside for growing ligno-cellulosic bioenergy crops or energy crops[13] (average increase of 193 million ha, between 2010 and 2100).

The IAMs diverge in the future development of pasture area in the baseline scenario. IMAGE and MESSAGE-GLOBIOM expect that the area of pastureland will increase by 109 million ha and 212 million ha, between 2010 and 2100. On the other hand, AIM/CGE, REMIND-MAGPIE and GCAM4 expect that pastureland will decrease by an average of 90 million ha from 2010 until 2100. In AIM/CGE and GCAM4, the decrease in pastureland is happening as a result of areas being set aside for growing energy crops.

For *2 °C scenarios* dynamics of agricultural land for food and feed production are affected by land demanding mitigation options such as bioenergy, avoided deforestation or afforestation. As a result of land needed for large scale bioenergy production and afforestation programs in the 2 °C scenarios, the use of land for food and feed production, pasture, and other natural land are generally expected to be reduced (see Figure 21). In IAMs, the median global allocation of land to ligno-cellulosic bioenergy crop production is 600 million ha in 2100, due to the demand for wood in energy production and active carbon dioxide removal from the atmosphere (BECCS) (see Section 5.1(b)). The land system can also contribute to climate change mitigation by increasing carbon stocks and reducing current emissions. Related to these mitigation efforts, the global forest area is expected to increase, in order to sequester more carbon through afforestation and reduce emissions related to deforestation events (see Section 5.1(c), for further details).

Land demanding mitigation options, including energy crops and afforestation, are expected by the IAMs to increase the pressures on the land system and generally occur at the expense of pastureland (average decrease of 493 million ha, from 2010 to 2100) and other natural land that is not cultivated (average decrease of 386 million ha, from 2010 to 2100). Pricing of non-CO_2 emissions from the livestock sector is also a reason for the reduction in pastureland in the models, in particular for greenhouse-gas-emission-intensive production systems (see Section 5.1(c) below, for further details). Loss of pastureland is expected to mainly take place in Latin America and the Caribbean, Middle East and Africa, as well as OECD. Loss of other natural land is also expected to be highly concentrated in Latin America and the Caribbean, Middle East, but also in the Reforming Economies of Eastern Europe and the Former Soviet Union. Regional mitigation pressures on the land systems, such as avoided deforestation restricts agricultural expansion in the 2 °C scenarios and leads to a reduction of agricultural land for food and feed purposes. The use of cropland for food and feed production generally decreases moderately in the IAMs (average decrease of 111 million ha between 2010 and 2100).

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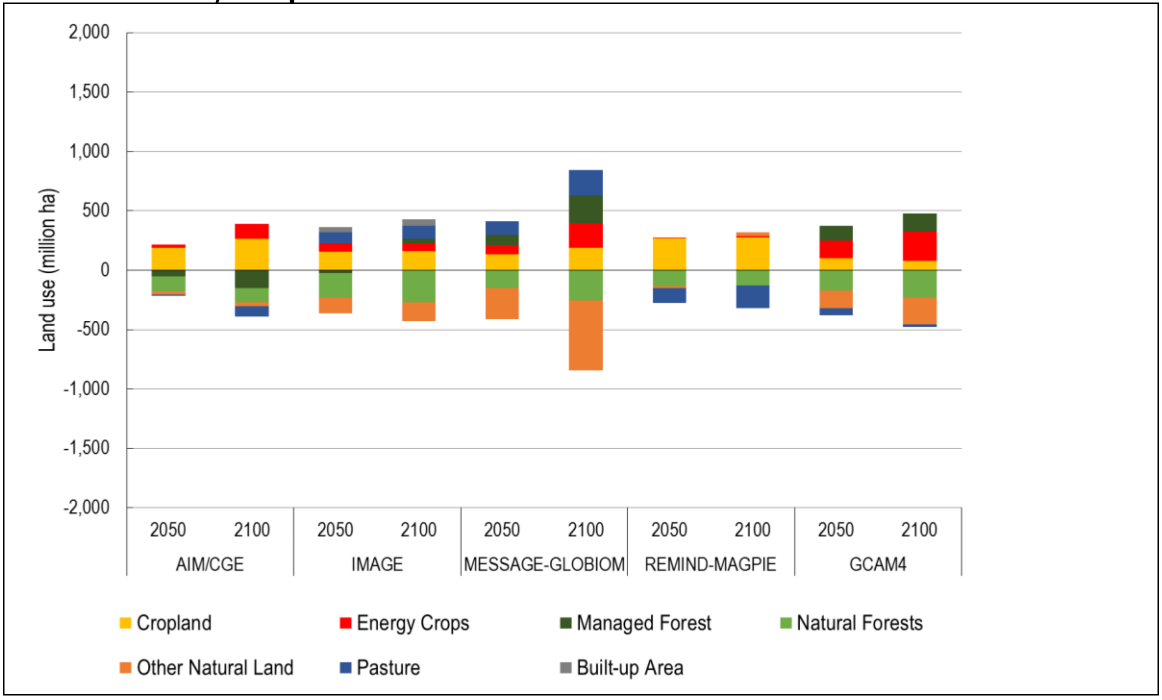
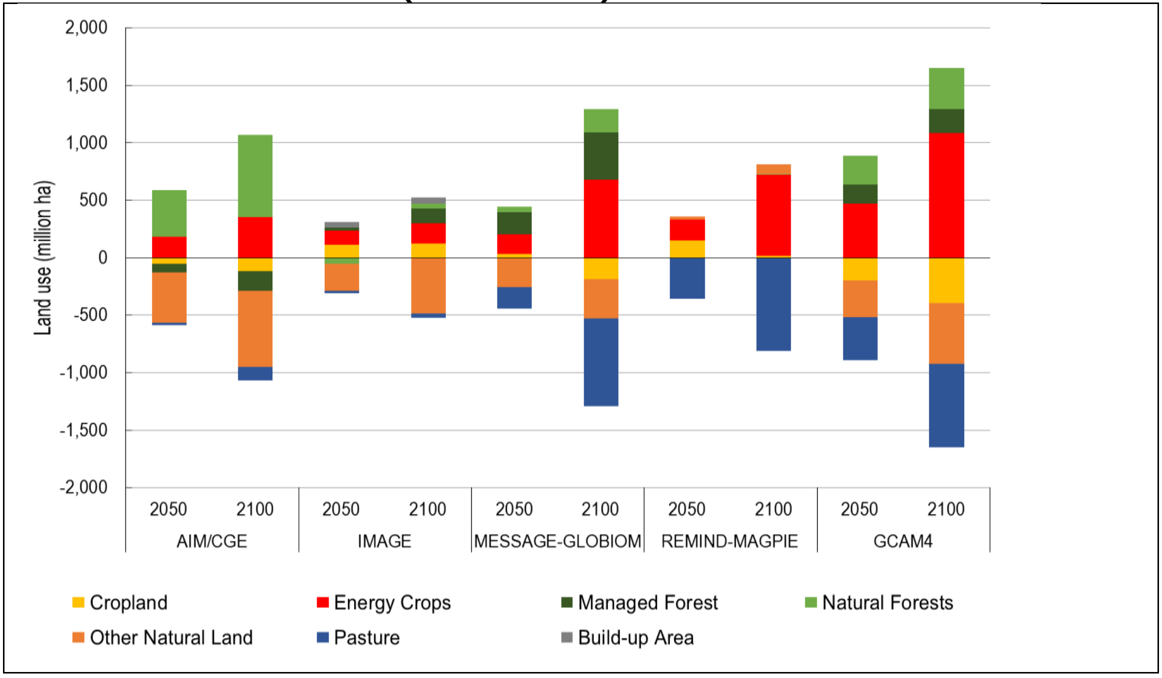
[13] Ligno-cellulosic bioenergy crops or energy crops here mean crops such as miscanthus, reed canary grass, and quickly growing tree species such as poplar and willow.

Figure 20. Future change in land use for a baseline scenario (SSP2 RCP-Baseline), in the five IAMs, compared to 2010 estimates.



A positive value indicates an increase in the type of land use for that year, compared to the 2010 situation; a negative value indicates a decrease. Source: Popp et al. (2017)

Figure 21. Future change in land use for the five IAMs as compared to 2010 estimates for a 2 °C scenario (SSP2 RCP-2.6).



Source: Popp et al. (2017)

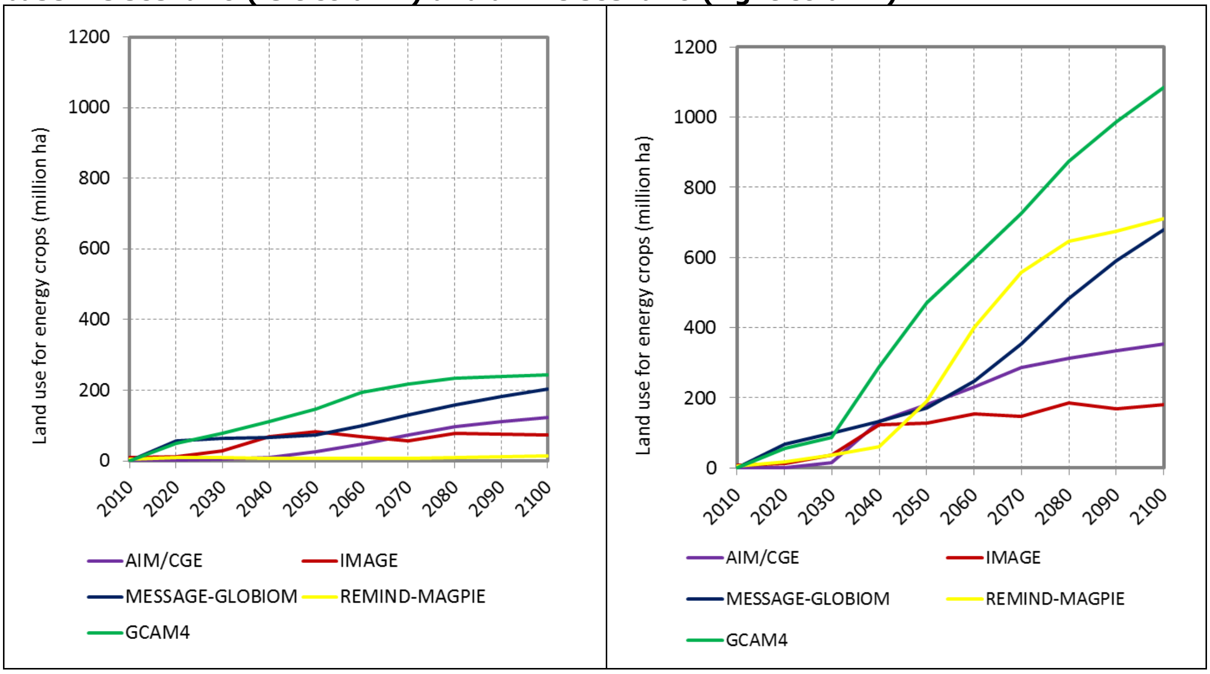
(b) How much land area would be needed to grow energy crops?

Dedicated energy crops are expected to play a critical role in 2 °C scenarios. The global area of land dedicated to energy crops, however, varies significantly across IAMs. The 2 °C scenarios project that, by 2100, between 180 million ha (IMAGE) and 1084 million ha (GCAM) are expected to be allocated to energy crops — compared to currently less than one million ha.

The IAMs, generally, expect dedicated second-generation bioenergy crops, or energy crops, to be developed already under the *baseline scenario* (the SSP2 RCP-Baseline scenario). The global amount of land set aside for energy crops by 2100 is assessed to be between 15 and 250 million ha (see Figure 22 left column).

For 2 °C scenarios, all IAMs assessed by Popp et al. (2017) show that dedicated second-generation bioenergy crops will play a critical role in nearly all mitigation scenarios, as they provide an option to reduce emissions from the electricity and transport sectors and allow for active carbon dioxide removal from the atmosphere if combined with carbon capture and storage (BECCS) (see Figure 22, right column). However, the range of future global land area set aside for energy crops varies significantly across models for scenarios with a likely chance of staying below 2 °C. In 2050, the IAMs globally allocate between 130 million ha (IMAGE) and 470 million ha (GCAM4) of land to dedicated energy crops. In 2100, the IAMs allocate globally between 180 million ha (IMAGE) and 1080 million ha (GCAM4) of land to dedicated energy crops.

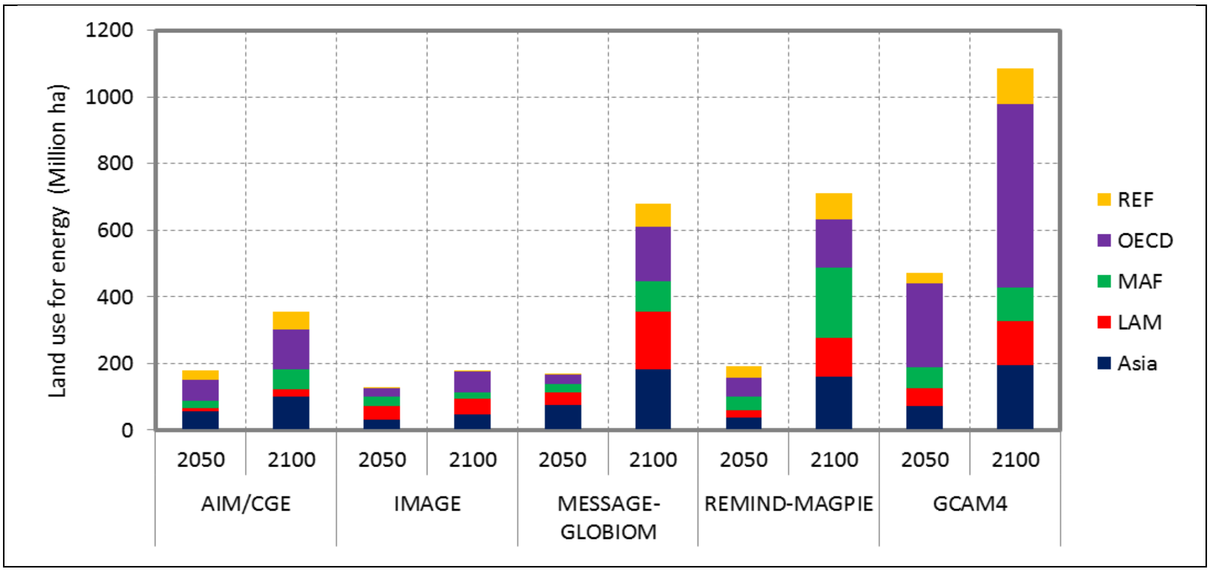
Figure 22. Future change in dedicated energy crops for the five IAMs for the baseline scenario (left column) and a 2 °C scenario (right column).



Source: Popp et al. (2017)

The regional distribution of dedicated energy crops varies significantly between the models, but some similarities can be noted between the IAMs (see Figure 23). Generally, energy crops are expected to be particularly concentrated in OECD, ASIA, and the Middle East and Africa as a result of high yields potentials combined with relatively low development costs of energy crop plantations for these regions. AIM/CGE, IMAGE, and GCAM4 all expect that the lion’s share of dedicated energy crops share of dedicated energy plantations would come from the OECD regions by 2100. The models expect that the OECD region will contribute to 34% (AIM/CGE), 35% (IMAGE), and 51% (GCAM4) of the global land dedicated to energy crops. MESSAGE-GLOBIOM and REMIND-MAGPIE also expect that large areas of energy crops will be developed in the OECD region, but they expect the lion's share to come from Asia (27% of global energy crops for MESSAGE-GLOBIOM) and Middle East and Africa (30% of global energy crops for REMIND-MAGPIE). IMAGE, MESSAGE-GLOBIOM and REMIND-MAGPIE all expect the smallest amount of dedicated energy crops from the countries from the Reforming Economies of Eastern Europe and the Former Soviet Union.

Figure 23. Future regional distribution of dedicated energy crops for a 2 °C scenario.



Regional aggregations are as follows: REF: Reforming Economies of Eastern Europe and the Former Soviet Union; OECD: OECD 90 and EU Member States and candidates; ASIA: most Asian countries with the exception of the Middle East, Japan and Former Soviet Union states; MAF: Middle East and Africa; LAM: Latin America and the Caribbean.
Source: Popp et al. (2017).

(c) How do these strategies impact the forest area?

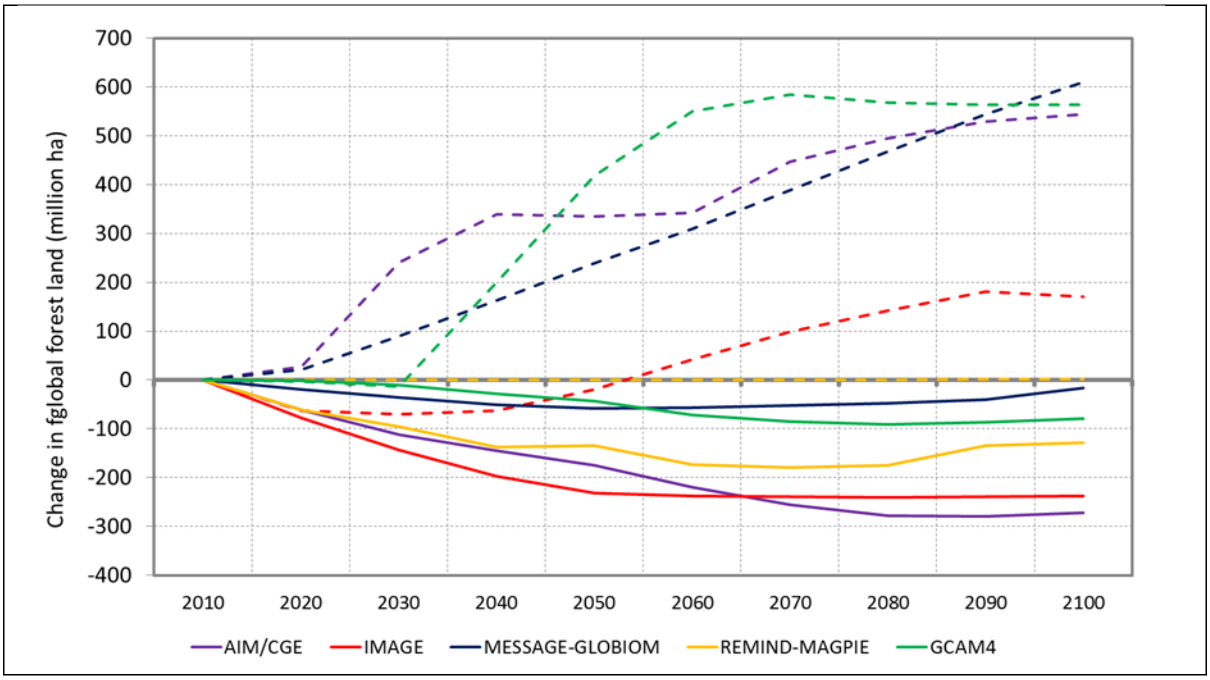
The forest area is a function of possible reforestation/afforestation actions, on the one hand, and possible deforestation resulting from bio-energy production. On average, most models see a reduction of deforestation rates. The net loss of forest land would need to be halted by 2030 and change to an increase in forest area thereafter. The projected increase in forest area varies significantly between IAMs. The increase in global forest area ranges from a moderate 150 million ha (REMIND-MAGPIE), to a significant 820 million ha (AIM/CGE) for the year 2100, compared to the situation of 2010.

Forests are generally expected by the IAMs to play a significant role in mitigating climate change and it is expected that 2 °C scenarios will lead to an increase in forest area as compared to baseline scenarios without mitigation efforts (the SSP2 Baseline scenario) (see Figure 24).

The global forest area is expected by all the IAMs to decrease over time in a baseline scenario. Net loss of forest land is only expected to be reached between 2050 and 2090, after which some gains in net forest area are expected. The global forest area in 2100 is expected to be reduced by 20 million ha (MESSAGE-GLOBIOM) to 270 million ha (AIM/CGE) as compared to 2010 levels. Given that forests globally cover roughly 3900 million ha today, this decrease is relatively small and generally based on the expectation that the deforestation rate will decrease in an SSP2 scenario (Fricko et al., 2017).

In 2 °C scenarios, the net loss of forest areas is expected to be halted at the global level by 2030, and all IAMs expect that the net forest area will be increasing from 2030 onwards. As such, the global forest area is expected to increase, compared to developments under the baseline scenario (see Figure 24). Overall, avoided deforestation and increased afforestation efforts are expected to lead to a moderate increase of the global forest area (average increase of 183 million ha from 2010 to 2100). However, the increase of the global forest area diverges significantly between the models. The IAMs expect that the global forest area will be increased by 150 million ha (REMIND-MAGPIE) to 820 million ha (AIM/CGE) by the year 2100 and relative to the baseline scenario.

Figure 24. Future change in global forest land for the baseline (solid lines) and a 2 °C scenario (dotted lines).



Source: Popp et al. (2017)

In terms of the regional distribution of the expected increase in the global forest area for 2 °C scenarios, all IAMs expect that the lion’s share of the increase in forest area would come from the regions of Latin America and the Caribbean (LAM) and the Middle East and Africa (MAF) (see Table 11). The models expect that these two regions will contribute by as much as 100% (REMIND-MAGPIE), 80% (GCAM), 75% (MESSAGE-GLOBIOM), 51% (IMAGE), and 48% (AIM/CGE) to the global increase in the forest land. Other regions for which the individual models are expecting high increases in forest area are Asia (IMAGE), OECD (AIM/CGE and MESSAGE-GLOBIOM), and the reforming economies of eastern Europe and the Former Soviet Union (REF) (GCAM). The AIM/CGE, IMAGE, MESSAGE-GLOBIOM and REMIND-MAGPIE models all expect the smallest increase in forest land to take place in the REF region.

It should be noted that the increase in forest area, in the IAMs, is driven by three main mitigation options: the demand for wood for bioenergy purposes, the need to reduce emissions from deforestation and the need to increase afforestation to sequester carbon. The extent to which the various IAM models rely on these three general mitigation options varies significantly due to model assumptions and data sources being used.

Table 11. Regional change in forest land area (million ha) for a 2 °C scenario compared to a baseline scenario. All estimates are for the year 2100.

	IMAGE	MESSAGE-GLOBIOM	GCAM4	REMIND-MAGPIE	AIM/CGE
OECD	19	101	-48	3	191
REF	14	2	154	-11	147
ASIA	90	53	24	7	83
MEF	119	140	284	116	173
LAM	167	330	229	35	223
World	408	627	643	150	817

Source: Popp et al. (2017)

5.2 What could be food price implications of the 2 °C scenarios?

As shown in other publications, additional land-use for mitigation has impacts on food prices and biodiversity. However, food availability and agricultural commodity prices may differ significantly, depending on how mitigation policies are implemented and which sectors are specifically targeted by a policy measure.

In a baseline scenario, SSP2, SSP4 and SSP5 show either flat or slightly falling world market prices for crops and livestock products by 2100, compared to 2005 (see Figure 25).

For 2 °C (450 ppm CO_2eq) scenarios, land based mitigation measures are expected to cause world market prices to increase relative to 2005 in the SSP2 (+110%), SSP5 (+170%) and SSP4 (+570%) scenarios as a result of the uniform carbon tax[14], changes in agricultural management, increased bioenergy production, and land used for afforestation. In SSP1, mitigation hardly influences food prices due to a general 'food first' policy, which can restrict agricultural expansion to avoid deforestation, but further only allows bioenergy on areas not needed for food and feed production. In general, considerable agricultural intensification (such as in SSP5), responses in agricultural trade (such as in SSP4 and SSP5), and changes in total production and consumption (such as in SSP2) have the capability to diminish food price reactions.

It can be noted that the uncertainty across models for food prices is significant, with GCAM projecting much larger increases in the mitigation cases than other models. These price effects in GCAM are due to the strong dependence on afforestation and bioenergy as mitigation options, leading to significant land competition. Due to this uncertainty, the selection of marker models strongly influences the ranking of this variable, unlike previous results. In the mitigation cases, all models show food prices that are lower in SSP1 and higher in SSP3 than the SSP2 in 2100. Food prices in SSP4 are smaller than (GCAM) or equal to (AIM) prices in SSP2. Food prices in the SSP5 are higher than the SSP2 in all models. While the qualitative ordering is robust across models, the magnitude of change differs significantly across models, with GCAM showing higher increases due to mitigation than any other model.

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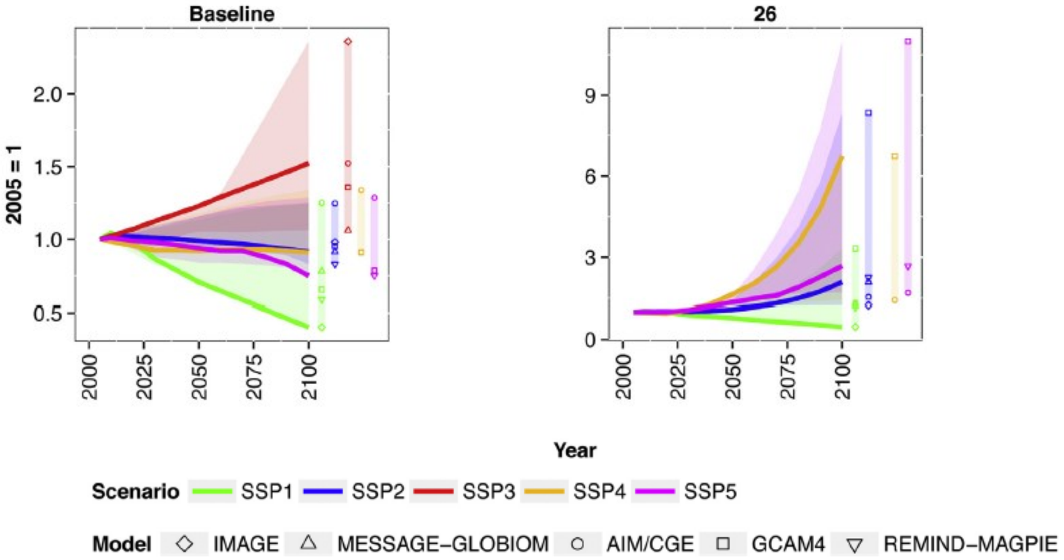
[14] A tax is implemented in the models such that the sources of emissions are taxed according to a specific carbon price.

Figure 25. Change in world market prices [2005 = 1] aggregated across all crop and livestock commodities of the five SSP marker scenarios for the baseline (left column) and RCP-2.6 (right column) cases



Note that the left and right columns have individual scales. Coloured lines indicate the marker model results for each SSP. Coloured bars indicate the range of data in 2100 across all marker and non-marker projections for each SSP (models are depicted by icon). Source: Popp et al. (2017).

It should be noted that in the assessment by Popp et al. (2017) mitigation policies are generally implemented through a uniform global carbon tax that directly implies a negative effect on agriculture and livestock production through the greenhouse gas emission intensity of the production system. As implemented for the assessment, climate mitigation policies directly impact the total level of revenue for agriculture producers through changes in the cost of production (pricing of emissions).

It has been argued that the way that mitigation policies are implemented can have large implications on sectorial and regional food production. Havlík et al. (2014) have shown that the carbon price effects on food availability can largely differentiate whether a carbon price targets non-CO_2 emissions from agriculture or CO_2 emissions from land-use change. Havlík et al. (2015) have also shown that agricultural commodity prices would be affected very differently depending on the targeted sectors. If only non-CO_2 emissions from the agriculture sector were to be targeted by a carbon price, the impact on prices would be about half compared to the idealised policy implementation (costing of greenhouse gas emissions from all economic sectors) by 2030. Targeting only CO_2 emissions from land-use change and forest management would have almost no effect on crop prices, and also the effect on livestock prices would be just about a third compared to the idealised policy implementation.

5.3 What could be the biodiversity implications of the 2 °C scenarios?

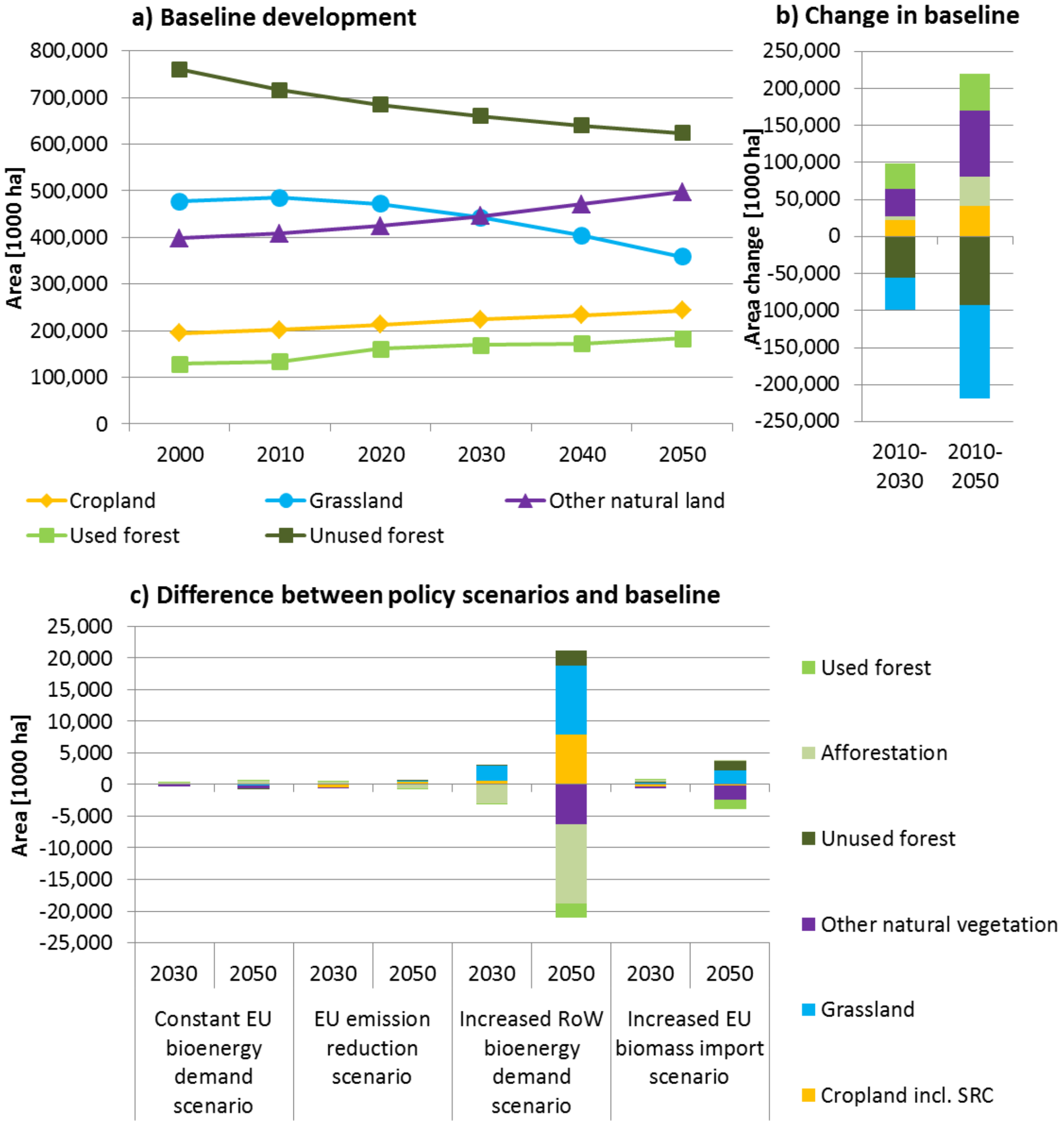
Some models project that under the baseline scenario, developments may lead to the conversion of a significant number of high biodiversity areas (220 million ha, globally, over the period from 2010 to 2050). Staying at or below the 2 °C temperature increase may have a relatively limited negative impact on the conversion of high biodiversity areas, and may only lead to an additional 20 million ha of high biodiversity areas being converted, globally, by 2050.

One study that assesses the potential biodiversity implications of global mitigation scenarios is that by Böttcher et al. (2016). While the study has an EU policy focus, it also assesses the biodiversity implications of global mitigation scenarios. In terms of biodiversity, the study assesses the conversion of land with a high biodiversity value (HBV), based on the UNEP-UCMC biodiversity atlas for a Baseline and number of policy scenarios. The study uses the development of high biodiversity value (HBV) as a key indicator for assessing the effects on biodiversity, as the conversion of these areas is very likely related to biodiversity loss. This applies to forests, grazing land and other natural land, in particular.

Overall, the baseline scenario has been designed to be as comparable as possible to the 2013 EU Reference Scenario (Commission, 2013) used in the 2014 IA report (Commission, 2014). The ‘Increased RoW bioenergy demand scenario’ represented a situation in which joint global efforts are taken to reduce greenhouse gas emissions beyond 2020, thereby enhancing the development of the bioenergy sector for the RoW and the EU. The scenario assumes higher targets for the EU and the RoW, in terms of greenhouse gas emission reduction, in comparison to the baseline scenario. This in turn is expected to lead to globally increasing demand for biomass for energy purposes and globally increasing pressure to produce biomass resources. For RoW, the bioenergy demand is based on the 2015 Global Mitigation scenario (Labat et al., 2015) as jointly developed based on the POLES and GEM-E3 models. This scenario reflects that joint international actions are taken to reduce global emissions in line with achieving the 2 °C objective and where all regions put into play actions that lead to a lower greenhouse gas emission pathway. For further details concerning the scenarios we refer to Forsell et al. (2016).

The study found that in the Rest of the World (RoW), the expected conversion of HBV areas was significantly higher in the Baseline development than the additional conversion of HBV areas for reaching the ‘Increased RoW bioenergy demand scenario’ (see Figure 26). As much as 220 million ha of HBV areas was expected to be converted during the period of 2010 until 2050 in the Baseline scenario development. Unused forests form the largest share of the areas impacted, followed by other natural land and grazing land. This can be compared to the development in the ‘Increased RoW bioenergy demand scenario’ where only an additional 20 million ha of HBV areas are expected to be converted.

Figure 26. Projected changes of HBV areas in RoW a) in the baseline, b) in the baseline between 2010 and 2030/2050 and c) in different scenarios and years compared to the baseline. Source: Böttcher et al. (2016).



5.4 How much forest land would be dedicated to producing biomass for the energy sector and how intensively would forests be used, under the 2 °C scenarios?

To achieve the 2 °C target, by the end of the century, a roughly projected 184 million ha of forest land would be required to directly produce roundwood for the bioenergy sector, and the global intensity of forest resource use would increase from 30% in 2010 to 57% by 2100.
Few studies have assessed the amount of forest land that in a 2 °C scenario can be expected to be set aside strictly to grow biomass for energy purposes or the amount of roundwood of industrial roundwood quality that is expected to be harvested directly for bioenergy purposes[15]. One of the reasons for this is that except for traditional fuelwood[16], almost no forest areas are currently being set aside to grow woody biomass only for energy purposes (Keenan et al., 2015). In addition to fuelwood, it is rather forest residues[17] (such as branches and tops) and industrial by-products[18] (such as wood chips and sawdust) that are currently the main biomass sources being used for energy purposes.

One study that has assessed the global impact of a 2 °C scenario on the future woody biomass use and forest land dedicated to energy production is that of Lauri et al. (2017). The study utilised the GLOBIOM modelling framework to assess the effect of achieving the 2 °C objective on future forest harvest levels and the use of woody biomass feedstocks for energy and material purposes. The assessment found that in a baseline scenario without strong mitigation efforts (i.e. SSP2 RCP-Baseline), only minor amounts of roundwood are expected to be harvested directly for energy use and the global forest harvest level is expected to only increase from roughly 3.7 Gm^3 in 2010 to 4.1 Gm^3 in 2100 (see Figure 27). The main underlying reason for this development is that fuelwood consumption is expected to be phased out by 2080 to electricity and modern cooking fuels by income growth, urbanisation and active investment policies (Fricko et al., 2017). This development would free-up significant forest resources for the development of the material sector. Furthermore, the strong increase in the production of woody materials (see Figure 29) is expected to deliver large quantities of industrial by-products and supply the expected growth in the bioenergy sector.

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[15] Roundwood that is directly used for energy production in small or large conversion facilities. This category does not include the wood biomass obtained from industrial by-products, nor firewood (household use of energy for fuel), nor forest residues. As such, the category accounts for stem wood that is of industrial roundwood quality and could be used for material purposes by the forest-based sector but that is instead being used for energy production.

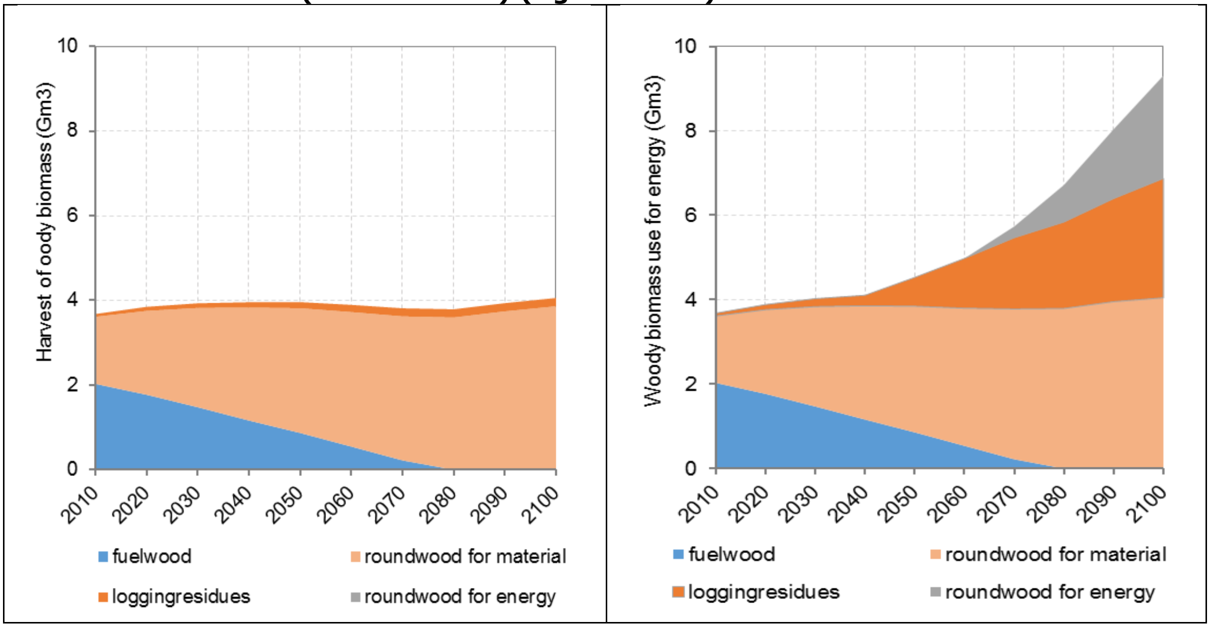
[16] Fuelwood is roundwood being used as fuel for such purposes as cooking, heating or power production. It includes wood harvested from main stems, branches and other parts of trees (where these are harvested for fuel) and wood that is used for the production of charcoal (e.g. in pit kilns and portable ovens), wood pellets and other agglomerates.

[17] Forest residues are typically leftover branches, stumps and stem tops from logging operations – thinning or final felling, chipped and mostly used for energy production. Forest residues are gathered from the logging site and forwarded to the roadside to be loaded on truck for long distance transport.

[18] Industrial by-products include industrial chips, sawdust, shavings, trimmings and bark. They are supplied as by-products available in proportions from the processes of wood products industry, mainly sawmilling but also wood based panels and joinery production. Industrial by-products have to be clean and they are not altered by any chemical process. They are important raw materials for pulp, wood based panels (Particleboard, MDF/HDF) and wood pellet production as well as in bioenergy production as such.

On the contrary, for 2 °C the study found that roundwood and logging residues are expected to become important sources of feedstock for the bioenergy sector. As much as 2.4 Gm^3 of roundwood and 2.8 Gm^3 of logging residues are expected to globally be used directly for energy purposes by the year 2100. This can be compared to the total global harvest of fuelwood in 2010, which has been estimated to be in the range of 2.1 Gm^3 in 2010 (FAOSTAT). In terms of area, the study assessed that by 2100 roughly 184 million ha of forest land would be dedicated to grow roundwood specifically dedicated for the bioenergy sector, and that logging residues would be expected to be harvested from as much as 911 million ha of forest land. The main underlying reason for this development is that by-products are not sufficient to satisfy the strong development of high bioenergy demand after 2060 and that intensification in the use of forest can be done to a generally low cost.

Figure 27. Global harvest of woody biomass from forests to be used for material and energy purposes in the baseline scenario (SSP2 RCP-Baseline) (left column) and the 2 °C scenario (SSP2 RCP-2.6) (right column)



It should be noted that roundwood here refers to both pulplogs and sawlogs being harvested for material and energy use. Also, estimates do not include woody biomass from dedicated bioenergy crops. Source: Lauri et al. (2017).

The increase in bioenergy demand, under the 2 °C scenario, is also expected to increase the intensity with which the world's forests resources will be used. The intensity of forest resources use is a common measure of how intensively forest resources are being used and it is calculated as the share of the annual increment that is being harvested (i.e. harvest / forest growth)[19]. As of 2010, the global intensity of forest resources use was 30% and is expected to increase to roughly 35% by 2100 in the baseline scenario and to 57% for the 2 °C scenario (see Figure 28). Under the 2 °C scenario, the intensity of forest resource use is expected to increase the most in South America, Asia and Africa. The reason for this is high forest productivity, relatively low production costs, and it's the regions where large amounts of roundwood are expected to be used directly for energy purposes. In Africa, Asia and South America, the intensity in forest resource use is expected to increase from 21% to 51% (Africa), from 55% to 86% (Asia) and from 27% to 48% (South America), by 2100, compared to 2010 levels. In North America, Russia and EU28, the intensity is expected to only increase modestly from 43% to 55% (Africa), from 20% to 30% (Asia) and from 86% to 95% (South America), by 2100, compared to 2100.

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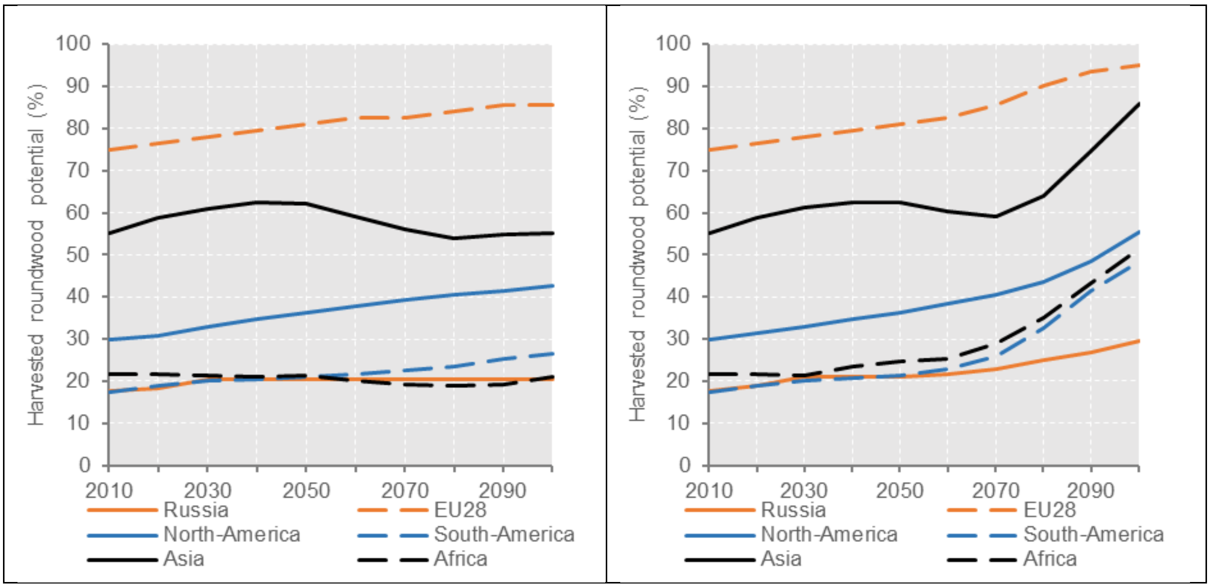
[19] Harvest intensity is measured as the percentage of the forest growth that is being harvested for a specific year. The intensity of forest resources use thereby depends on the share of available forest area that used for production as well as on the intensity of forest management in the total forest area (i.e. managed forests, afforested areas and primary forests). It should be noted that the intensity measure commonly only covers roundwood removals and not the harvest of forest residues.

Figure 28. Regional intensity of forest resource use for the baseline (SSP2 RCP-Baseline) (left column) and the 2 °C scenario (SSP2 RCP-2.6) (right column)



Intensity of forest resource use is defined as the share of forest growth that is being harvested. Source: Lauri et al. (2017).

5.5 What are the implications of the 2 °C scenarios for forest-based industries?

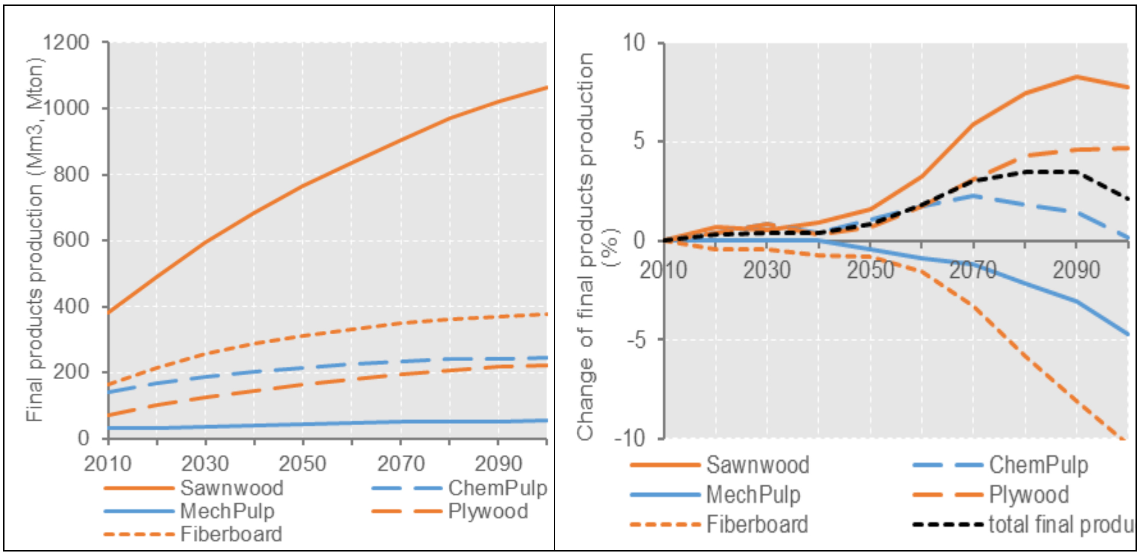
No significant distortions to woody material markets are expected, and there could even be beneficial effects for certain forest-based industries.

Development of the bioenergy sector in-line with a likely chance of staying below 2 °C is commonly expected to lead to high competition for biomass resources and distortion of woody biomass material use. However, relatively few studies have assessed the effects of staying below 2 °C on the global woody biomass use and implications for the forest based industries. Raunikar et al. (2010) studied the effects of IPCC SRES scenarios (IPCC 2000) on the global woody biomass use by using the Global Forest Products Model (GFPM). They conclude that moving from a low mitigation scenario (A2) to a high mitigation scenario (A1B) would lead to 3 times higher roundwood prices and 15% decrease in the woody biomass material use as of 2060. Favero and Mendelsohn (2013) studied the effects of reaching different radiative forcing levels on the global woody biomass use 2010–2100 by using the Global Timber Model (GTM) and the WITCH integrated assessment model. They concluded that mitigation efforts necessary for reaching a radiative forcing level of 2.5 W/m^2 would lead to almost 2 times higher roundwood prices and 80% decrease in the woody biomass material use as of 2100, as compared to the development foreseen for a baseline scenario with no mitigation policies that would lead to a radiative forcing level of 6.6 W/m^2 radiative forcing level.

On the contrary, a study by Lauri et al. (2017) is showing that the bioenergy sector can be developed in-line with a likely chance of staying below 2 °C without significant distortions to the production of woody materials. Furthermore, the study shows that such a development of the bioenergy sector could even have beneficial effects for certain forest industries (see Figure 29). Overall, staying below 2 °C is expected to lead to a small increase in the total global production of harvested woody materials (less than 5%). The reason for this is that the higher bioenergy demand is expected to increase the demand for forest industry by-products (e.g. sawdust, wood chips, bark), making material production more profitable for industries that provide large shares of by-products and thereby compensating the cost effect of increased competition for raw materials.

The study applied the GLOBIOM modelling framework and analysed the implications of scenario in-line with a likely chance of staying below 2 °C (450 ppm CO_2eq scenarios – i.e. SSP2 RCP-2.6), and a baseline scenario without mitigation efforts (SSP2 RCP-Baseline). A strong growth in the production of woody materials, and in particular sawnwood, is expected for the baseline scenario. The main drivers of the increase in the production of sawnwood are population and GDP growth, which lead to significant increases in the demand for sawnwood in Asia, South America and Africa. An increased bioenergy demand level was found to be particularly beneficial for industries producing sawnwood and plywood, as the demand for their wood-based industrial by-products (i.e. sawdust, shavings, bark, industrial wood chips) increases. These industrial sectors can provide large amounts of by-products to be used for bioenergy production and the increase in bioenergy demand leads to an increase in the production of the sawnwood and plywood commodities. On the other hand, the higher bioenergy demand is expected to inhibit fibreboard and mechanical pulp production as these are major consumers of industrial by-products. It can be noted that the same effect of increasing bioenergy demand on the material sectors was already shown to be the case for the EU in Forsell et al. (2016).

Figure 29. Expected global production of woody materials under the baseline scenario (SSP2 RCP-Baseline) (left column), and change in production (in %) under the 2 °C scenario (SSP2 RCP-2.6), compared to the baseline scenario (right column).



For the right column, positive values show that production is expected to be higher in the 2 °C scenario than in the baseline scenario. Source: Lauri et al. (2017).

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Appendix I: Overview of models, scenarios and regions

Table 12: Overview of models, scenarios and covered regions for total greenhouse gas emissions, before scenario selection, i.e. including models with projections up to 2050 (GEM-E3 only has projections up to 2030)

Delayed (2020)		Number of scenarios						
Region	**Number of models**	**DNE21+ V.12A**	**GEM-E3_IPTS_World**	**IMAGE 2.4**	**MESSAGE V.4**	**POLES GECO2016**	**REMIND 1.5**	**WITCH 2013**
ASIA	6	0	1	1	1	1	1	1
Brazil	3	0	1	1	0	1	0	0
Canada	3	0	1	1	0	1	0	0
China	6	0	1	1	1	1	1	1
EU	5	0	1	1	0	1	1	1
India	5	0	1	1	0	1	1	1
Indonesia	3	0	1	1	0	1	0	0
Japan	4	0	1	1	0	1	1	0
LAM	6	0	1	1	1	1	1	1
MAF	6	0	1	1	1	1	1	1
Mexico	3	0	1	1	0	1	0	0
OECD90+EU	5	0	0	1	1	1	1	1
REF	5	0	1	1	1	1	0	1
ROWO	1	0	0	0	0	0	1	0
Russia	4	0	1	1	0	1	1	0
South Africa	3	0	1	1	0	1	0	0
South Korea	3	0	1	1	0	1	0	0
Turkey	3	0	1	1	0	1	0	0
USA	6	0	1	1	1	1	1	1
World	6	0	1	1	1	1	1	1

Delayed (2030)		Number of scenarios						
Region	**Number of models**	**DNE21+ V.12A**	**GEM-E3_IPTS_World**	**IMAGE 2.4**	**MESSAGE V.4**	**POLES GECO2016**	**REMIND 1.5**	**WITCH 2013**
ASIA	4	2	0	0	2	0	2	2
Brazil	1	2	0	0	0	0	0	0
Canada	1	2	0	0	0	0	0	0
China	4	2	0	0	2	0	2	2
EU	3	2	0	0	0	0	2	2
India	3	2	0	0	0	0	2	2
Indonesia	0	0	0	0	0	0	0	0
Japan	2	2	0	0	0	0	2	0
LAM	4	2	0	0	2	0	2	2
MAF	4	2	0	0	2	0	2	2
Mexico	1	2	0	0	0	0	0	0
OECD90+EU	4	2	0	0	2	0	2	2
REF	3	2	0	0	2	0	0	2
ROWO	1	0	0	0	0	0	2	0
Russia	2	2	0	0	0	0	2	0
South Africa	0	0	0	0	0	0	0	0
South Korea	1	2	0	0	0	0	0	0
Turkey	1	2	0	0	0	0	0	0
USA	4	2	0	0	2	0	2	2
World	4	2	0	0	2	0	2	2

		Delayed (2030)		Delayed (2020)					
Model	Region	AMPERE2-450-FullTech-HST	AMPERE2-450-FullTech-LST	LIMITS-RefPol-450	Delayed 450	2C	Count (2020)	Count (2030)	Count (total)
DNE21+ V.12A	ASIA	x	x				0	2	2
GEM-E3_IPTS_World	ASIA				x		1	0	1
IMAGE 2.4	ASIA			x			1	0	1
MESSAGE V.4	ASIA	x	x	x			1	2	3
POLES GECO2016	ASIA					x	1	0	1
REMIND 1.5	ASIA	x	x	x			1	2	3
WITCH2013	ASIA	x	x	x			1	2	3
DNE21+ V.12A	Brazil	x	x				0	2	2
GEM-E3_IPTS_World	Brazil				x		1	0	1
IMAGE 2.4	Brazil			x			1	0	1
MESSAGE V.4	Brazil						0	0	0
POLES GECO2016	Brazil					x	1	0	1
REMIND 1.5	Brazil						0	0	0
WITCH2013	Brazil						0	0	0
DNE21+ V.12A	Canada	x	x				0	2	2
GEM-E3_IPTS_World	Canada				x		1	0	1
IMAGE 2.4	Canada			x			1	0	1
MESSAGE V.4	Canada						0	0	0
POLES GECO2016	Canada					x	1	0	1
REMIND 1.5	Canada						0	0	0
WITCH2013	Canada						0	0	0
DNE21+ V.12A	China	x	x				0	2	2

		Delayed (2030)		Delayed (2020)					
Model	**Region**	**AMPERE2-450-FullTech-HST**	**AMPERE2-450-FullTech-LST**	**LIMITS-RefPol-450**	**Delayed 450**	**2C**	**Count (2020)**	**Count (2030)**	**Count (total)**
GEM-E3_IPTS_World	China				x		1	0	1
IMAGE 2.4	China			x			1	0	1
MESSAGE V.4	China	x	x	x			1	2	3
POLES GECO2016	China					x	1	0	1
REMIND 1.5	China	x	x	x			1	2	3
WITCH2013	China	x	x	x			1	2	3
DNE21+ V.12A	EU	x	x				0	2	2
GEM-E3_IPTS_World	EU				x		1	0	1
IMAGE 2.4	EU			x			1	0	1
MESSAGE V.4	EU						0	0	0
POLES GECO2016	EU					x	1	0	1
REMIND 1.5	EU	x	x	x			1	2	3
WITCH2013	EU	x	x	x			1	2	3
DNE21+ V.12A	India	x	x				0	2	2
GEM-E3_IPTS_World	India				x		1	0	1
IMAGE 2.4	India			x			1	0	1
MESSAGE V.4	India						0	0	0
POLES GECO2016	India					x	1	0	1
REMIND 1.5	India	x	x	x			1	2	3
WITCH2013	India	x	x	x			1	2	3
DNE21+ V.12A	Japan	x	x				0	2	2
GEM-E3_IPTS_World	Japan				x		1	0	1

		Delayed (2030)		Delayed (2020)					
Model	**Region**	**AMPERE2-450-FullTech-HST**	**AMPERE2-450-FullTech-LST**	**LIMITS-RefPol-450**	**Delayed 450**	**2C**	**Count (2020)**	**Count (2030)**	**Count (total)**
IMAGE 2.4	Japan			x			1	0	1
MESSAGE V.4	Japan						0	0	0
POLES GECO2016	Japan					x	1	0	1
REMIND 1.5	Japan	x	x	x			1	2	3
WITCH2013	Japan						0	0	0
DNE21+ V.12A	LAM	x	x				0	2	2
GEM-E3_IPTS_World	LAM				x		1	0	1
IMAGE 2.4	LAM			x			1	0	1
MESSAGE V.4	LAM	x	x	x			1	2	3
POLES GECO2016	LAM					x	1	0	1
REMIND 1.5	LAM	x	x	x			1	2	3
WITCH2013	LAM	x	x	x			1	2	3
DNE21+ V.12A	MAF	x	x				0	2	2
GEM-E3_IPTS_World	MAF				x		1	0	1
IMAGE 2.4	MAF			x			1	0	1
MESSAGE V.4	MAF	x	x	x			1	2	3
POLES GECO2016	MAF					x	1	0	1
REMIND 1.5	MAF	x	x	x			1	2	3
WITCH2013	MAF	x	x	x			1	2	3
DNE21+ V.12A	Mexico	x	x				0	2	2
GEM-E3_IPTS_World	Mexico				x		1	0	1
IMAGE 2.4	Mexico			x			1	0	1
MESSAGE V.4	Mexico						0	0	0

		Delayed (2030)		Delayed (2020)					
Model	Region	AMPERE2-450-FullTech-HST	AMPERE2-450-FullTech-LST	LIMITS-RefPol-450	Delayed 450	2C	Count (2020)	Count (2030)	Count (total)
POLES GECO2016	Mexico					x	1	0	1
REMIND 1.5	Mexico						0	0	0
WITCH2013	Mexico						0	0	0
DNE21+ V.12A	OECD90+EU	x	x				0	2	2
GEM-E3_IPTS_World	OECD90+EU						0	0	0
IMAGE 2.4	OECD90+EU			x			1	0	1
MESSAGE V.4	OECD90+EU	x	x	x			1	2	3
POLES GECO2016	OECD90+EU					x	1	0	1
REMIND 1.5	OECD90+EU	x	x	x			1	2	3
WITCH2013	OECD90+EU	x	x	x			1	2	3
DNE21+ V.12A	REF	x	x				0	2	2
GEM-E3_IPTS_World	REF				x		1	0	1
IMAGE 2.4	REF			x			1	0	1
MESSAGE V.4	REF	x	x	x			1	2	3
POLES GECO2016	REF					x	1	0	1
REMIND 1.5	REF						0	0	0
WITCH2013	REF	x	x	x			1	2	3
DNE21+ V.12A	Russia	x	x				0	2	2
GEM-E3_IPTS_World	Russia				x		1	0	1
IMAGE 2.4	Russia			x			1	0	1
MESSAGE V.4	Russia						0	0	0
POLES GECO2016	Russia					x	1	0	1
REMIND 1.5	Russia	x	x	x			1	2	3

		Delayed (2030)		Delayed (2020)					
Model	**Region**	**AMPERE2-450-FullTech-HST**	**AMPERE2-450-FullTech-LST**	**LIMITS-RefPol-450**	**Delayed 450**	**2C**	**Count (2020)**	**Count (2030)**	**Count (total)**
WITCH2013	Russia						0	0	0
DNE21+ V.12A	South Korea	x	x				0	2	2
GEM-E3_IPTS_World	South Korea				x		1	0	1
IMAGE 2.4	South Korea			x			1	0	1
MESSAGE V.4	South Korea						0	0	0
POLES GECO2016	South Korea					x	1	0	1
REMIND 1.5	South Korea						0	0	0
WITCH2013	South Korea						0	0	0
DNE21+ V.12A	Turkey	x	x				0	2	2
GEM-E3_IPTS_World	Turkey				x		1	0	1
IMAGE 2.4	Turkey			x			1	0	1
MESSAGE V.4	Turkey						0	0	0
POLES GECO2016	Turkey					x	1	0	1
REMIND 1.5	Turkey						0	0	0
WITCH2013	Turkey						0	0	0
DNE21+ V.12A	USA	x	x				0	2	2
GEM-E3_IPTS_World	USA				x		1	0	1
IMAGE 2.4	USA			x			1	0	1

		Delayed (2030)		Delayed (2020)					
Model	Region	AMPERE2-450-FullTech-HST	AMPERE2-450-FullTech-LST	LIMITS-RefPol-450	Delayed 450	2C	Count (2020)	Count (2030)	Count (total)
MESSAGE V.4	USA	x	x	x			1	2	3
POLES GECO2016	USA					x	1	0	1
REMIND 1.5	USA	x	x	x			1	2	3
WITCH2013	USA	x	x	x			1	2	3
DNE21+ V.12A	World	x	x				0	2	2
GEM-E3_IPTS_World	World				x		1	0	1
IMAGE 2.4	World			x			1	0	1
MESSAGE V.4	World	x	x	x			1	2	3
POLES GECO2016	World					x	1	0	1
REMIND 1.5	World	x	x	x			1	2	3
WITCH2013	World	x	x	x			1	2	3
DNE21+ V.12A	Indonesia						0	0	0
GEM-E3_IPTS_World	Indonesia				x		1	0	1
IMAGE 2.4	Indonesia			x			1	0	1
MESSAGE V.4	Indonesia						0	0	0
POLES GECO2016	Indonesia					x	1	0	1
REMIND 1.5	Indonesia						0	0	0
WITCH2013	Indonesia						0	0	0
DNE21+ V.12A	South Africa						0	0	0
GEM-E3_IPTS_World	South Africa				x		1	0	1
IMAGE 2.4	South Africa			x			1	0	1

		Delayed (2030)		Delayed (2020)					
Model	**Region**	**AMPERE2-450-FullTech-HST**	**AMPERE2-450-FullTech-LST**	**LIMITS-RefPol-450**	**Delayed 450**	**2C**	**Count (2020)**	**Count (2030)**	**Count (total)**
MESSAGE V.4	South Africa						0	0	0
POLES GECO2016	South Africa					x	1	0	1
REMIND 1.5	South Africa						0	0	0
WITCH2013	South Africa						0	0	0
DNE21+ V.12A	ROWO						0	0	0
GEM-E3_IPTS_World	ROWO						0	0	0
IMAGE 2.4	ROWO						0	0	0
MESSAGE V.4	ROWO						0	0	0
POLES GECO2016	ROWO						0	0	0
REMIND 1.5	ROWO	x	x	x			1	2	3
WITCH2013	ROWO						0	0	0

Table 13: Overview of models, scenarios and covered regions for total greenhouse gas emissions, after scenario selection, i.e. only including models with projections up to 2100

Delayed (2020)		Number of scenarios						
Region	Number of models	DNE21+ V.12A	GEM-E3_IPTS_World	IMAGE 2.4	MESSAGE V.4	POLES GECO2016	REMIND 1.5	WITCH 2013
ASIA	4	0	0	1	1	0	1	1
Brazil	1	0	0	1	0	0	0	0
Canada	1	0	0	1	0	0	0	0
China	4	0	0	1	1	0	1	1
EU	3	0	0	1	0	0	1	1
India	3	0	0	1	0	0	1	1
Indonesia	1	0	0	1	0	0	0	0
Japan	2	0	0	1	0	0	1	0
LAM	4	0	0	1	1	0	1	1
MAF	4	0	0	1	1	0	1	1
Mexico	1	0	0	1	0	0	0	0
OECD90+EU	4	0	0	1	1	0	1	1
REF	3	0	0	1	1	0	0	1
ROWO	1	0	0	0	0	0	1	0
Russia	2	0	0	1	0	0	1	0
South Africa	1	0	0	1	0	0	0	0
South Korea	1	0	0	1	0	0	0	0
Turkey	1	0	0	1	0	0	0	0
USA	4	0	0	1	1	0	1	1
World	4	0	0	1	1	0	1	1

Delayed (2030)		Number of scenarios						
Region	**Number of models**	**DNE21+ V.12A**	**GEM-E3_IPTS_World**	**IMAGE 2.4**	**MESSAGE V.4**	**POLES GECO2016**	**REMIND 1.5**	**WITCH 2013**
ASIA	3	0	0	0	2	0	2	2
Brazil	0	0	0	0	0	0	0	0
Canada	0	0	0	0	0	0	0	0
China	3	0	0	0	2	0	2	2
EU	2	0	0	0	0	0	2	2
India	2	0	0	0	0	0	2	2
Indonesia	0	0	0	0	0	0	0	0
Japan	1	0	0	0	0	0	2	0
LAM	3	0	0	0	2	0	2	2
MAF	3	0	0	0	2	0	2	2
Mexico	0	0	0	0	0	0	0	0
OECD90+EU	3	0	0	0	2	0	2	2
REF	2	0	0	0	2	0	0	2
ROWO	1	0	0	0	0	0	2	0
Russia	1	0	0	0	0	0	2	0
South Africa	0	0	0	0	0	0	0	0
South Korea	0	0	0	0	0	0	0	0
Turkey	0	0	0	0	0	0	0	0
USA	3	0	0	0	2	0	2	2
World	3	0	0	0	2	0	2	2

		Delayed (2030)		Delayed (2020)			
Model	**Region**	**AMPERE2-450-FullTech-HST**	**AMPERE2-450-FullTech-LST**	**LIMITS-RefPol-450**	**Count (Delayed 2020)**	**Count (Delayed 2030)**	**Count**
DNE21+ V.12A	ASIA				0	0	0
GEM-E3_IPTS_World	ASIA				0	0	0
IMAGE 2.4	ASIA			x	1	0	1
MESSAGE V.4	ASIA	x	x	x	1	2	3
POLES GECO2016	ASIA				0	0	0
REMIND 1.5	ASIA	x	x	x	1	2	3
WITCH2013	ASIA	x	x	x	1	2	3
DNE21+ V.12A	Brazil				0	0	0
GEM-E3_IPTS_World	Brazil				0	0	0
IMAGE 2.4	Brazil			x	1	0	1
MESSAGE V.4	Brazil				0	0	0
POLES GECO2016	Brazil				0	0	0
REMIND 1.5	Brazil				0	0	0
WITCH2013	Brazil				0	0	0
DNE21+ V.12A	Canada				0	0	0
GEM-E3_IPTS_World	Canada				0	0	0
IMAGE 2.4	Canada			x	1	0	1
MESSAGE V.4	Canada				0	0	0
POLES GECO2016	Canada				0	0	0
REMIND 1.5	Canada				0	0	0
WITCH2013	Canada				0	0	0
DNE21+ V.12A	China				0	0	0
GEM-E3_IPTS_World	China				0	0	0
IMAGE 2.4	China			x	1	0	1
MESSAGE V.4	China	x	x	x	1	2	3
POLES GECO2016	China				0	0	0
REMIND 1.5	China	x	x	x	1	2	3
WITCH2013	China	x	x	x	1	2	3
DNE21+ V.12A	EU				0	0	0
GEM-E3_IPTS_World	EU				0	0	0
IMAGE 2.4	EU			x	1	0	1
MESSAGE V.4	EU				0	0	0
POLES GECO2016	EU				0	0	0
REMIND 1.5	EU	x	x	x	1	2	3

		Delayed (2030)		Delayed (2020)			
Model	**Region**	**AMPERE2-450-FullTech-HST**	**AMPERE2-450-FullTech-LST**	**LIMITS-RefPol-450**	**Count (Delayed 2020)**	**Count (Delayed 2030)**	**Count**
WITCH2013	EU	x	x	x	1	2	3
DNE21+ V.12A	India				0	0	0
GEM-E3_IPTS_World	India				0	0	0
IMAGE 2.4	India			x	1	0	1
MESSAGE V.4	India				0	0	0
POLES GECO2016	India				0	0	0
REMIND 1.5	India	x	x	x	1	2	3
WITCH2013	India	x	x	x	1	2	3
DNE21+ V.12A	Japan				0	0	0
GEM-E3_IPTS_World	Japan				0	0	0
IMAGE 2.4	Japan			x	1	0	1
MESSAGE V.4	Japan				0	0	0
POLES GECO2016	Japan				0	0	0
REMIND 1.5	Japan	x	x	x	1	2	3
WITCH2013	Japan				0	0	0
DNE21+ V.12A	LAM				0	0	0
GEM-E3_IPTS_World	LAM				0	0	0
IMAGE 2.4	LAM			x	1	0	1
MESSAGE V.4	LAM	x	x	x	1	2	3
POLES GECO2016	LAM				0	0	0
REMIND 1.5	LAM	x	x	x	1	2	3
WITCH2013	LAM	x	x	x	1	2	3
DNE21+ V.12A	MAF				0	0	0
GEM-E3_IPTS_World	MAF				0	0	0
IMAGE 2.4	MAF			x	1	0	1
MESSAGE V.4	MAF	x	x	x	1	2	3
POLES GECO2016	MAF				0	0	0
REMIND 1.5	MAF	x	x	x	1	2	3
WITCH2013	MAF	x	x	x	1	2	3
DNE21+ V.12A	Mexico				0	0	0
GEM-E3_IPTS_World	Mexico				0	0	0
IMAGE 2.4	Mexico			x	1	0	1
MESSAGE V.4	Mexico				0	0	0
POLES GECO2016	Mexico				0	0	0

		Delayed (2030)		Delayed (2020)			
Model	**Region**	**AMPERE2-450-FullTech-HST**	**AMPERE2-450-FullTech-LST**	**LIMITS-RefPol-450**	**Count (Delayed 2020)**	**Count (Delayed 2030)**	**Count**
REMIND 1.5	Mexico				0	0	0
WITCH2013	Mexico				0	0	0
DNE21+ V.12A	OECD90+EU				0	0	0
GEM-E3_IPTS_World	OECD90+EU				0	0	0
IMAGE 2.4	OECD90+EU			x	1	0	1
MESSAGE V.4	OECD90+EU	x	x	x	1	2	3
POLES GECO2016	OECD90+EU				0	0	0
REMIND 1.5	OECD90+EU	x	x	x	1	2	3
WITCH2013	OECD90+EU	x	x	x	1	2	3
DNE21+ V.12A	REF				0	0	0
GEM-E3_IPTS_World	REF				0	0	0
IMAGE 2.4	REF			x	1	0	1
MESSAGE V.4	REF	x	x	x	1	2	3
POLES GECO2016	REF				0	0	0
REMIND 1.5	REF				0	0	0
WITCH2013	REF	x	x	x	1	2	3
DNE21+ V.12A	Russia				0	0	0
GEM-E3_IPTS_World	Russia				0	0	0
IMAGE 2.4	Russia			x	1	0	1
MESSAGE V.4	Russia				0	0	0
POLES GECO2016	Russia				0	0	0
REMIND 1.5	Russia	x	x	x	1	2	3
WITCH2013	Russia				0	0	0
DNE21+ V.12A	South Korea				0	0	0
GEM-E3_IPTS_World	South Korea				0	0	0
IMAGE 2.4	South Korea			x	1	0	1
MESSAGE V.4	South Korea				0	0	0
POLES GECO2016	South Korea				0	0	0
REMIND 1.5	South Korea				0	0	0
WITCH2013	South Korea				0	0	0
DNE21+ V.12A	Turkey				0	0	0

		Delayed (2030)		Delayed (2020)			
Model	**Region**	**AMPERE2-450-FullTech-HST**	**AMPERE2-450-FullTech-LST**	**LIMITS-RefPol-450**	**Count (Delayed 2020)**	**Count (Delayed 2030)**	**Count**
GEM-E3_IPTS_World	Turkey				0	0	0
IMAGE 2.4	Turkey			x	1	0	1
MESSAGE V.4	Turkey				0	0	0
POLES GECO2016	Turkey				0	0	0
REMIND 1.5	Turkey				0	0	0
WITCH2013	Turkey				0	0	0
DNE21+ V.12A	USA				0	0	0
GEM-E3_IPTS_World	USA				0	0	0
IMAGE 2.4	USA			x	1	0	1
MESSAGE V.4	USA	x	x	x	1	2	3
POLES GECO2016	USA				0	0	0
REMIND 1.5	USA	x	x	x	1	2	3
WITCH2013	USA	x	x	x	1	2	3
DNE21+ V.12A	World				0	0	0
GEM-E3_IPTS_World	World				0	0	0
IMAGE 2.4	World			x	1	0	1
MESSAGE V.4	World	x	x	x	1	2	3
POLES GECO2016	World				0	0	0
REMIND 1.5	World	x	x	x	1	2	3
WITCH2013	World	x	x	x	1	2	3
DNE21+ V.12A	Indonesia				0	0	0
GEM-E3_IPTS_World	Indonesia				0	0	0
IMAGE 2.4	Indonesia			x	1	0	1
MESSAGE V.4	Indonesia				0	0	0
POLES GECO2016	Indonesia				0	0	0
REMIND 1.5	Indonesia				0	0	0
WITCH2013	Indonesia				0	0	0
DNE21+ V.12A	South Africa				0	0	0
GEM-E3_IPTS_World	South Africa				0	0	0
IMAGE 2.4	South Africa			x	1	0	1
MESSAGE V.4	South Africa				0	0	0

		Delayed (2030)		Delayed (2020)			
Model	**Region**	**AMPERE2-450-FullTech-HST**	**AMPERE2-450-FullTech-LST**	**LIMITS-RefPol-450**	**Count (Delayed 2020)**	**Count (Delayed 2030)**	**Count**
POLES GECO2016	South Africa				0	0	0
REMIND 1.5	South Africa				0	0	0
WITCH2013	South Africa				0	0	0
DNE21+ V.12A	ROWO				0	0	0
GEM-E3_IPTS_World	ROWO				0	0	0
IMAGE 2.4	ROWO				0	0	0
MESSAGE V.4	ROWO				0	0	0
POLES GECO2016	ROWO				0	0	0
REMIND 1.5	ROWO	x	x	x	1	2	3
WITCH2013	ROWO				0	0	0

Appendix II: Region definitions

OECD90+EU Includes the OECD 1990 countries as well as EU members and candidates.
Albania, Australia, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Fiji, Finland, France, French Polynesia, Germany, Greece, Guam, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Macedonia, Montenegro, Netherlands, New Caledonia, New Zealand, Norway, Poland, Portugal, Romania, Samoa, Serbia, Slovakia, Slovenia, Solomon Islands, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States of America, Vanuatu

REF Countries from the Reforming Economies of the Former Soviet Union.
Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan

ASIA The region includes most Asian countries with the exception of the Middle East, Japan and Former Soviet Union states.
Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China, China Hong Kong SAR, China Macao SAR, Democratic People's Republic of Korea, East Timor, India, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Singapore, Sri Lanka, Taiwan, Thailand, Viet Nam

MAF This region includes the countries of the Middle East and Africa.
Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Cote d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Oman, Qatar, Reunion, Rwanda, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Syrian Arab Republic, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Yemen, Zambia, Zimbabwe

LAM This region includes the countries of Latin America and the Caribbean.
Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela

Appendix III: Reduction targets

Table 14: Projected regional greenhouse gas emissions (including LULUCF CO_2) by 2030 and 2050, relative to 2010, in delayed mitigation 450 ppm CO_2eq scenarios (negative numbers denote a reduction), using the full set of models (including models with projections up to 2050, and for 2030 including GEM-E3, which has projections up to 2030). Source: LIMITS and AMPERE databases (Kriegler, 2014c; Riahi et al., 2015)

GHG emissions relative to 2010 (%)		2030						2050					
Scenario	**Region**	**Min**	**10th percentile**	**Mean**	**Median**	**90th percentile**	**Max**	**Min**	**10th percentile**	**Mean**	**Median**	**90th percentile**	**Max**
Delayed (2020)	ASIA	-31	-17	2	5	20	21	-63	-63	-52	-52	-41	-39
Delayed (2020)	China	-22	-18	0	-3	20	21	-78	-78	-64	-67	-47	-45
Delayed (2020)	EU	-49	-44	-35	-33	-29	-29	-77	-76	-75	-74	-73	-73
Delayed (2020)	India	-13	10	43	51	69	81	-36	-36	-24	-25	-11	-8
Delayed (2020)	Japan	-36	-33	-26	-24	-21	-21	-95	-92	-84	-81	-77	-76
Delayed (2020)	LAM	-54	-52	-29	-36	0	17	-137	-114	-82	-71	-61	-59
Delayed (2020)	MAF	-21	-4	20	17	46	67	-43	-36	-13	-18	18	38
Delayed (2020)	OECD90+EU	-47	-41	-34	-30	-30	-29	-84	-84	-80	-81	-77	-76
Delayed (2020)	REF	-47	-40	-22	-15	-8	-5	-81	-80	-69	-72	-55	-50
Delayed (2020)	Russia	-37	-33	-23	-23	-14	-11	-93	-91	-75	-80	-58	-52
Delayed (2020)	USA	-64	-50	-38	-34	-31	-30	-88	-87	-85	-85	-84	-83
Delayed (2020)	World	-39	-26	-12	-10	0	2	-73	-70	-61	-59	-52	-47
Delayed (2030)	ASIA	9	15	28	33	37	37	-53	-52	-44	-48	-32	-27

GHG emissions relative to 2010 (%)		2030						2050					
Scenario	**Region**	**Min**	**10th percentile**	**Mean**	**Median**	**90th percentile**	**Max**	**Min**	**10th percentile**	**Mean**	**Median**	**90th percentile**	**Max**
Delayed (2030)	China	23	26	36	33	48	54	-64	-63	-58	-58	-52	-50
Delayed (2030)	EU	-12	-11	-5	-10	3	7	-85	-83	-74	-76	-64	-61
Delayed (2030)	India	53	61	79	92	93	93	-19	-16	-3	-8	12	17
Delayed (2030)	Japan	-22	-20	-12	-12	-4	-2	-77	-76	-75	-75	-73	-73
Delayed (2030)	LAM	-19	-9	7	14	17	18	-99	-90	-69	-63	-53	-51
Delayed (2030)	MAF	19	24	35	38	43	45	-105	-79	-34	-14	-5	-3
Delayed (2030)	OECD90+EU	-14	-14	-8	-9	-1	0	-84	-83	-76	-76	-68	-67
Delayed (2030)	REF	-17	-14	-4	-2	4	6	-83	-82	-75	-74	-70	-69
Delayed (2030)	Russia	-17	-15	-6	-6	3	5	-77	-77	-77	-77	-77	-77
Delayed (2030)	USA	-19	-18	-13	-14	-7	-5	-89	-88	-79	-79	-71	-70
Delayed (2030)	World	12	12	15	14	17	18	-69	-67	-56	-56	-45	-43

Appendix IV: Harmonisation

There are three harmonisation methods in the literature (Rogelj et al., 2011): offset harmonisation (a constant absolute factor to match 2010 emissions), uniform scaling harmonisation (a constant scaling factor to match 2010 emissions), and tapered scaling harmonisation (in which the scaling factor starts from the same point as the scaling harmonisation method, but the scaling is relaxed from the starting year over time until a match is reached). The projected 2030 emission level resulting from the offset harmonisation method generally lies in the middle of the range of outcomes of the three harmonisation methods (Rogelj et al., 2011), making it an appropriate choice for giving a first indication of the effect of harmonisation. However, for emissions that tend to go to zero, the offset method is no longer the approach that gives outcomes somewhere in the middle of the outcomes of all three harmonization methods. In such cases, a scaling harmonisation, or a tapered scaling harmonisation approach, could be used as alternative, as both approaches lead to a lower impact on emission projections due to scaling factors going to zero.

For this report, we focus on harmonizing the LULUCF CO_2 emissions only, and although these do tend to go to zero across models, we use a simple offset-method for harmonisation to show the other extreme, as opposed to no harmonisation. For example, China, the EU and the United States report carbon sinks for managed forests (US: -1 $GtCO_2$), which are projected to remain more or less the same in future. For these countries harmonisation to only LULUCF emissions/removals is expected to have a relatively large effect. Indeed, there are large differences between inventory data and IPCC/FAO model data in LULUCF emissions/removals estimates. This issue is well explained by Grassi et al. (2017), showing there is a difference of more than 3 $GtCO_2$ in 2010 in LULUCF emissions, largely due to different definitions and category inclusions.

Table 15. Median phase-out year for greenhouse gas emissions (upper table) and CO_2 emissions (lower table), per scenario and per region for the harmonisation cases (see Section 3.3).

Results are only presented for regions covered by at least two models. Numbers should be interpreted with care, as models generally report their emission projections in 10-year time steps.

Scenario	Region [no. of models]	No harmonisation	Harmonisation of CO_2 from LULUCF
Delayed 450	ASIA [4 models]	No phase-out	-
Delayed 450_2030	ASIA [4 models]	No phase-out	-
Delayed 450	China [4 models]	2100	2090
Delayed 450_2030	China [4 models]	2100	2095

Delayed 450	EU [3 models]	No phase-out	2080
Delayed 450_2030	EU [3 models]	No phase-out	2085
Delayed 450	India [3 models]	No phase-out	No phase-out
Delayed 450_2030	India [3 models]	No phase-out	No phase-out
Delayed 450	Japan [2 models]	2065	2065
Delayed 450_2030	Japan [2 models]	2075	2065
Delayed 450	LAM [4 models]	2075	-
Delayed 450_2030	LAM [4 models]	2070	-
Delayed 450	MAF [4 models]	No phase-out	-
Delayed 450_2030	MAF [4 models]	No phase-out	-
Delayed 450	OECD90+EU [4 models]	2080	-
Delayed 450_2030	OECD90+EU [4 models]	2085	-
Delayed 450	REF [3 models]	No phase-out	-
Delayed 450_2030	REF [3 models]	2080	-
Delayed 450	Russia [2 models]	2085	2077.5
Delayed 450_2030	Russia [2 models]	2060	2050
Delayed 450	USA [4 models]	2065	2060
Delayed 450_2030	USA [4 models]	2070	2060
Delayed 450	World [4 models]	2100	2085
Delayed 450_2030	World [4 models]	2100	2090

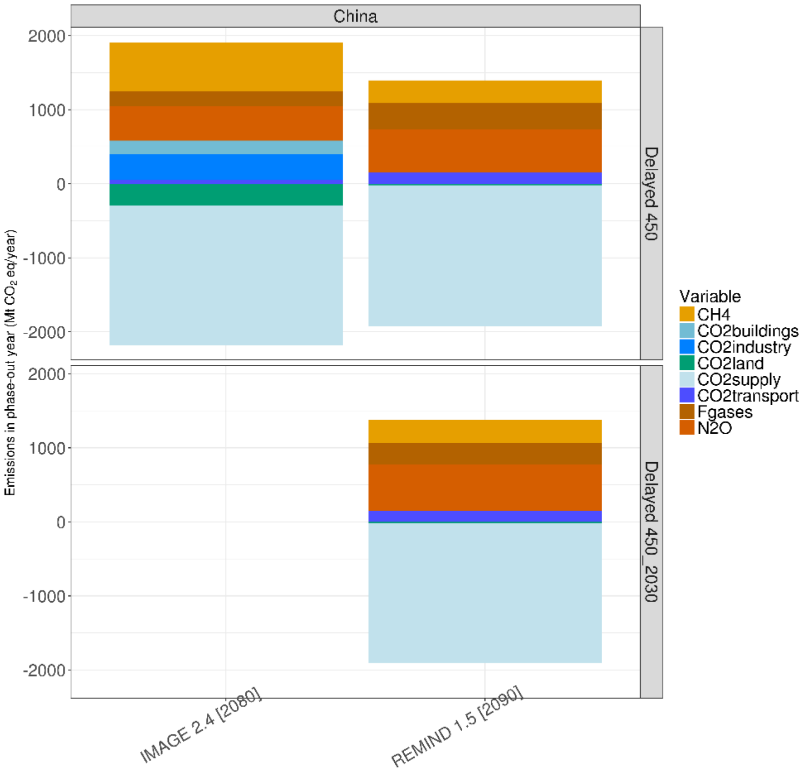
Scenario	**Region [no. of models]**	**No harmonisation**	**Harmonisation of CO_2 from LULUCF**
Delayed 450	ASIA [4 models]	2080	-
Delayed 450_2030	ASIA [4 models]	2085	-
Delayed 450	China [4 models]	2075	2070
Delayed 450_2030	China [4 models]	2090	2082.5
Delayed 450	EU [3 models]	2080	2060

Delayed 450_2030	EU [3 models]	2082.5	2067.5
Delayed 450	India [3 models]	2090	2080
Delayed 450_2030	India [3 models]	2100	2087.5
Delayed 450	Japan [2 models]	2055	2060
Delayed 450_2030	Japan [2 models]	2065	2060
Delayed 450	LAM [4 models]	2060	-
Delayed 450_2030	LAM [4 models]	2060	-
Delayed 450	MAF [4 models]	2060	-
Delayed 450_2030	MAF [4 models]	2062.5	-
Delayed 450	OECD90+EU [4 models]	2065	-
Delayed 450_2030	OECD90+EU [4 models]	2067.5	-
Delayed 450	REF [3 models]	No phase-out	-
Delayed 450_2030	REF [3 models]	2060	-
Delayed 450	Russia [2 models]	2080	2057.5
Delayed 450_2030	Russia [2 models]	2060	2045
Delayed 450	USA [4 models]	2060	2047.5
Delayed 450_2030	USA [4 models]	2060	2055
Delayed 450	World [4 models]	2065	2065
Delayed 450_2030	World [4 models]	2070	2060

Appendix V: Regional graphs of the breakdown of emissions in the phase-out year

This section shows graphs of the breakdown of emissions in the phase-out year, for countries that were not included in Section 3.4. Only regions covered by at least two models are shown. The following applies to all graphs: for models with multiple scenarios within a category (delayed 2030), the mean was taken (in the upper graph, separately for sets of scenarios with different phase-out years). The phase-out year for greenhouse gas emissions is indicated per model (upper graph). The lower graph also includes models that do not project a phase-out of greenhouse gas emissions and therefore did not show in the upper graph. See Figure 5 for a further explanation of the categories, if needed. Source: own calculations based on the LIMITS and AMPERE databases (Kriegler et al., 2014c; Riahi et al., 2015).

Figure 30. Breakdown of emissions (MtCO$_2$eq) in China, in the phase-out year for greenhouse gas (upper graph) and in 2100 (lower graph), for delayed mitigation 450 ppm CO$_2$eq scenarios (2020 and 2030).



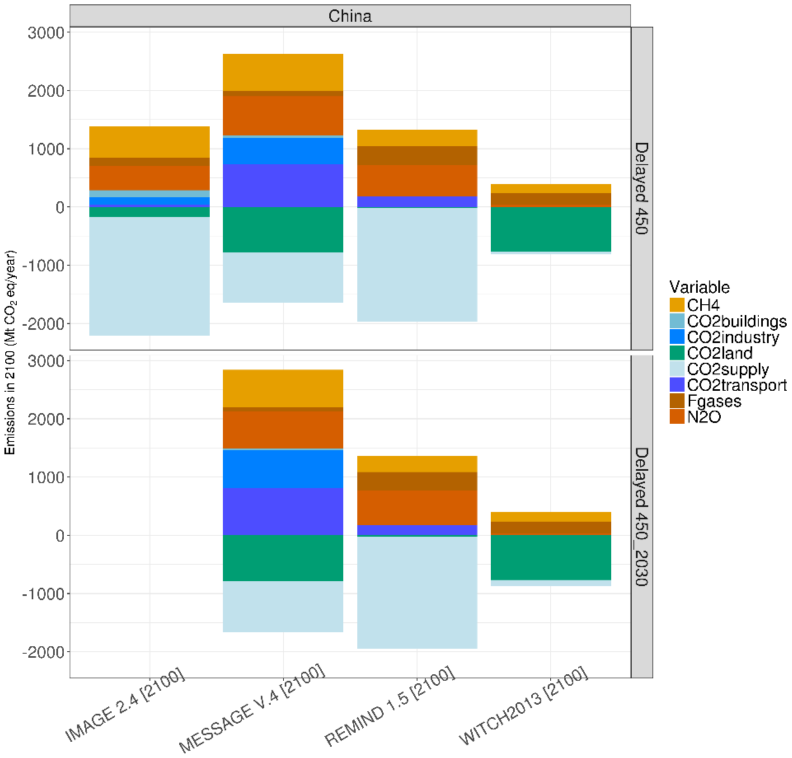


Figure 31. Breakdown of emissions ($MtCO_2eq$) in India, in 2100 , for delayed mitigation 450 ppm CO_2eq scenarios (2020 and 2030).

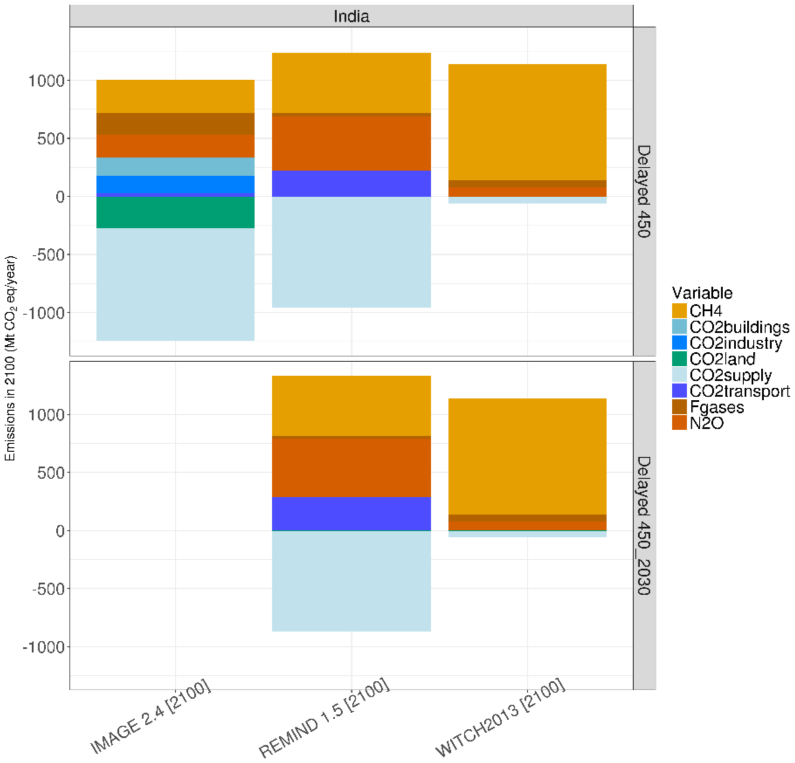


Figure 32. Breakdown of emissions (MtCO$_2$eq) in Japan, in the phase-out year for greenhouse gas (upper graph) and in 2100 (lower graph), for delayed mitigation 450 ppm CO$_2$eq scenarios (2020 and 2030).

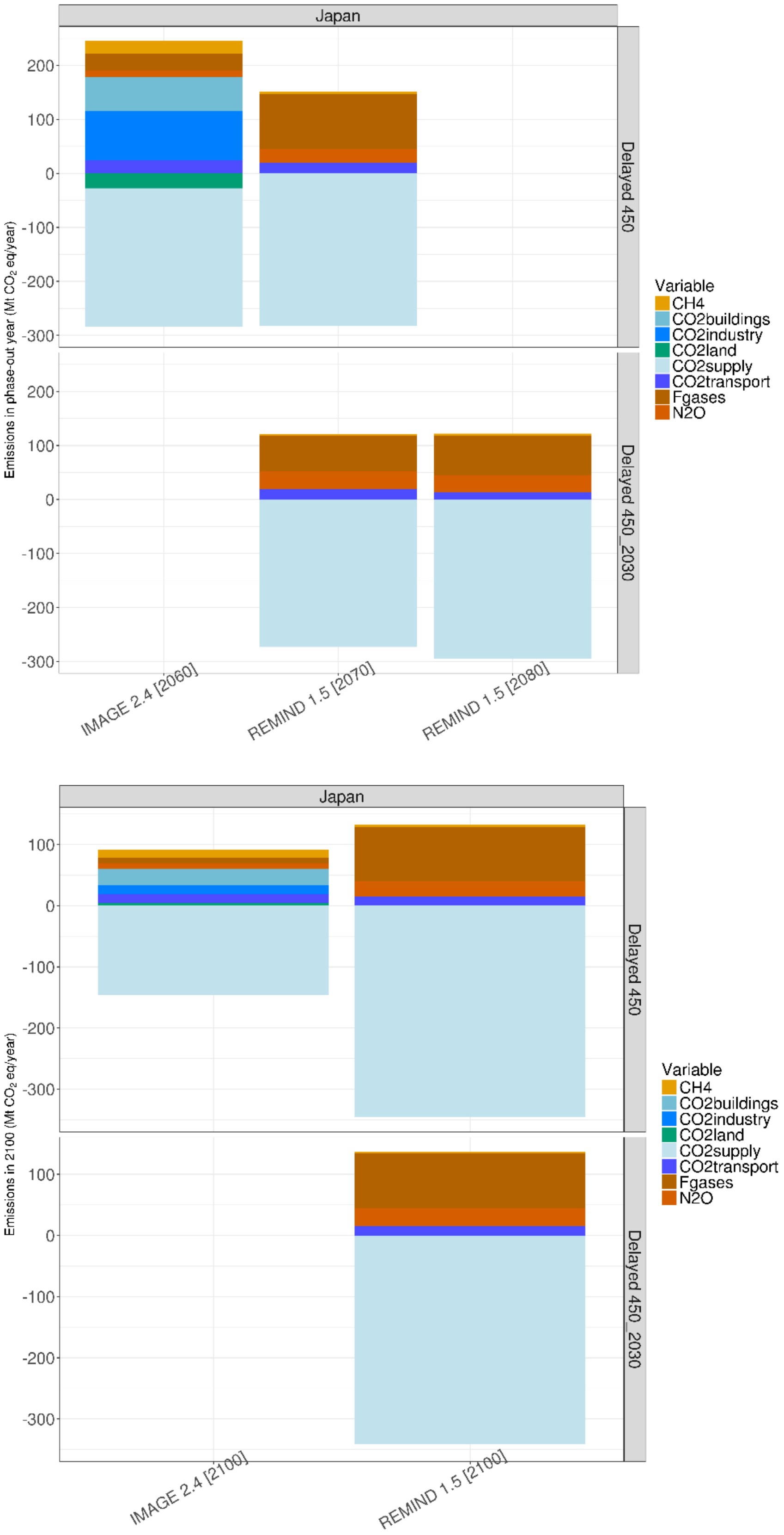


Figure 33. Breakdown of emissions ($MtCO_2eq$) in Russia, in 2100, for delayed mitigation 450 ppm CO_2eq scenarios (2020 and 2030).

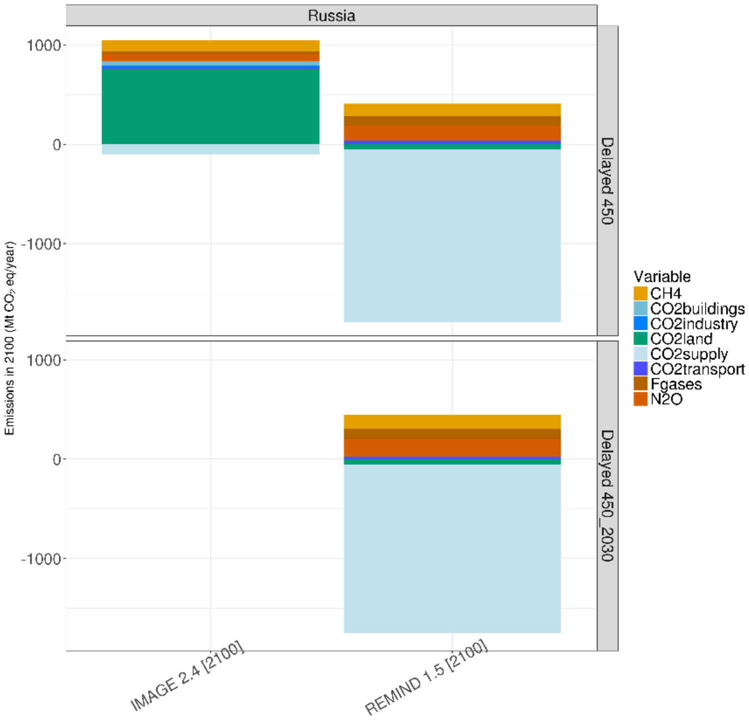


Figure 34. Breakdown of emissions ($MtCO_2eq$) in the United States, in the phase-out year, for greenhouse gas (upper graph) and in 2100 (lower graph), for delayed mitigation 450 ppm CO_2eq scenarios (2020 and 2030).