PBL Netherlands Environmental Assessment Agency

IMPLICATIONS OF LONG-TERM SCENARIOS FOR MEDIUM-TERM TARGETS (2050)

Authors

Detlef P. van Vuuren, Mariësse van Sluisveld and Andries F. Hof

November 2015

PBL

Implications of long-term scenarios for medium-term targets (2050)

The Hague/Bilthoven, 2015
PBL publication number: 1871
Norway Environment Agency report number: M-449|2015

Corresponding author
detlef.vanvuuren@pbl.nl

Authors
Detlef P. van Vuuren, Mariësse van Sluisveld and Andries F. Hof

Graphics
PBL Beeldredactie

Production coordination
and English-language editing
PBL Publishers and Plain English

Acknowledgements
This research was funded by the Norway Environment Agency.

PBL Netherlands Environmental Assessment Agency is the national institute for strategic policy analyses in the fields of the environment, nature and spatial planning. We contribute to improving the quality of political and administrative decision-making, by conducting outlook studies, analyses and evaluations in which an integrated approach is considered paramount. Policy relevance is the prime concern in all our studies. We conduct solicited and unsolicited research that is always independent and scientifically sound.

Contents

FINDINGS

In order to keep the increase in global mean temperature below 2 °C, with a *likely chance* (>66% probability), atmospheric greenhouse gas (GHG) concentrations need to remain at around 450 ppm CO_2eq or less. This roughly corresponds to a remaining overall emission budget of 1000 $GtCO_2$ (assuming emission reductions of non-CO_2 gases) (IPCC AR5). As scenarios without climate policy often lead to cumulative emissions in the order of 4000 $GtCO_2$, substantial cuts in anthropogenic greenhouse gas emissions would be required to achieve this goal. The Working Group III (WGIII) contribution to the most recent IPCC Assessment Report (AR5 - WGIII) indicates that *scenarios in which such concentration levels are achieved by 2100 are characterised by global greenhouse gas emission levels that are 40% to 70% lower in 2050 than in 2010, and near to or below zero by 2100.* These figures have been quoted frequently.

There are, however, a number of important questions still open in relation to the 2050 range. One important element is the use of so-called negative emissions, i.e. a situation in which anthropogenic activities lead to the removal of CO_2 from the atmosphere (e.g. as a result of bio-energy with CCS (BECCS) and afforestation/reforestation or direct air capture). If the total removal of CO_2 from the atmosphere because of negative emissions would exceed the total in anthropogenic emissions, a situation of 'net negative emissions' is created. This report discusses these questions based on the existing literature and an additional analysis of the scenario database that was developed for IPCC AR5 WGIII. The main findings are as follows.

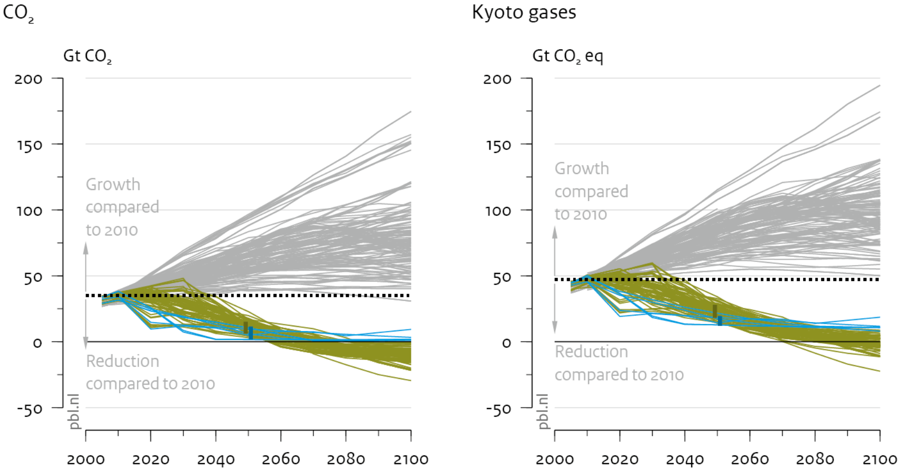
- **The target to keep the increase of global mean temperature below 2 °C corresponds to a carbon budget of around 1000 $GtCO_2$ from 2010 onwards.** The Fifth Assessment Report indicates that the 2 °C target corresponds to a maximum cumulative emission (carbon budget) of around 1000 $GtCO_2$ from 2010 onwards. The exact number depends strongly on policy choices and uncertainty. This includes the uncertainty in the climate system and the related degree of certainty (e.g. 66%) that policymakers would like to have of achieving the 2 °C target. It also involves an estimate on the reduction non-CO_2 gases.
- **All scenarios consistent with ambitious climate targets, such as the 2 °C target, will require major transitions in the worldwide energy system.** Scenario analysis shows that to achieve the necessary emission reductions major changes in current investment in energy systems are needed globally. The policies currently formulated are still not ambitious enough to achieve these transitions.
- **Most scenarios consistent with the 2 °C target in the scientific literature rely heavily on net negative CO_2 emissions.** AR5 WGIII investigated just over 100 scenarios with a likely probability of reaching the 2 °C target. Most of these scenarios showed net negative CO_2 emissions in the second half of the century. A net negative CO_2 emission scenario thus implies strong reliance on these technologies. Scenarios with net negative emissions often overshoot the 1000 $GtCO_2$ budget in 2050, and only return to the budget in the second half of the century.
- **The potential for negative CO_2 emissions in the second half of the century rests on assumptions concerning land and water use.** The activities most often considered in scenario analysis to create negative CO_2 emissions are BECCS and afforestation/reforestation. These activities require vast areas of land, possibly leading to competing claims from food production and biodiversity protection. Sustainable use of these activities thus requires careful consideration of the possible

impacts in other areas, related to expectations about future yields and land-use policies, for example.

- **The greenhouse gas emission reduction range of 40% to 70% by 2050, which is often quoted from the IPCC report, is not only due to uncertainty about technology performance or the climate system, but is also a reflection of policy choice. Scenarios that avoid net negative CO_2 emissions show emission reductions of at least 60% to 70% globally in 2050.** Meeting the 2 °C target with a likely probability requires limiting future cumulative emissions to around 1000 $GtCO_2$. Without net negative CO_2 emissions in the second half of the century – the only scenarios in the literature under which this objective is met – greenhouse gas emissions are reduced by at least 60% in 2050 (see Figure 1).
- **Similarly, policy choices that rely (or do not rely) on net negative emissions also have implications for emission reduction targets for specific regions.** The discussion on regional or national targets is even more complicated than on global targets, as they not only rely on biophysical, technical and economic considerations, but also on normative choices about the distribution of costs. For instance, the often quoted range of 80% to 95% emission reduction for high-income countries based on the Fourth Assessment Report refers to outcomes of studies taking 'fairness principles' into account (numbers refer to the allocation of assigned amounts before trade and, thus, not to domestic reductions). The Fifth Assessment Report shows that current studies based on allocation principles nevertheless result in similar outcomes. Clearly, emission reductions in the AR5 scenario database cannot be directly compared with such numbers, as the former show the results of cost-optimal emission reduction strategies. In general, also for targets at scales other than the global scale, decisions will need to be made regarding future use of net negative-emission strategies.
- **The emission reduction rates during the full 2015–2050 period have major long-term implications.** The fact that climate impacts are associated with cumulative CO_2 emissions (budget) implies that reaching specific targets does not depend solely on emissions in a single year, but on emissions throughout the entire period. In other words, emission reductions in the short term can significantly reduce the reduction rates in the long term (and vice versa). Scenarios with net negative emissions tend to overshoot by 2050, i.e. more than 100% of the available budget of about 1000 $GtCO_2$ has already been used – and net negative emissions after 2050 are needed to ensure that the budget is met in the long term. Scenarios without net negative emissions have generally used about 70% to 80% of the budget by 2050.

Figure 1

Emission of greenhouse gases under baseline and 2 °C scenarios



Scenarios

- Baseline
- 2 °C with negative emissions
- 2 °C without negative emissions
- 2010 emission level
- Range 2050

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

CO_2 emissions (left) and Kyoto greenhouse gas scenarios (right) assuming no new climate policies (grey) and scenarios consistent with the 2° C target, with net negative emissions (green) and without net negative emissions (blue).

- **Scenarios without net negative CO_2 emissions do not necessarily use less bio-energy.** Scenarios with net negative CO_2 emissions often rely on extensive use of BECCS. Scenarios that do not lead to net negative CO_2 emissions rely less on BECCS, but instead rely more on early deployment of renewable energy, bio-energy and nuclear power. The use of bio-energy is not necessarily less in scenarios without negative CO_2 emissions than those with negative CO_2 emissions, as bio-energy will be used more in transport and in power generation without CCS.
- **Scenarios consistent with the 1.5** °C **target typically exhibit even faster and more ambitious emission reductions before 2050 than 2 ° C scenarios, and more use of net negative emissions in the second half of the century.** This implies that reducing emissions faster in the short term leaves the option of little or no net negative emissions open – as well as the option of reaching a 1.5 ° C target by the end of the century. The latter, however, would also require net negative emissions.

FULL RESULTS

1 Introduction

In order to keep the increase in global mean temperature below 2 °C, with a *likely chance* (>66% probability), atmospheric greenhouse gas (GHG) concentrations need to remain at around 450 ppm CO_2eq or less. To achieve this, substantial cuts in anthropogenic greenhouse gas emissions will be required. More precisely, the WGIII contribution to the most recent IPCC Assessment Report (AR5 WGIII) indicates that scenarios reaching such concentration levels by 2100 are characterised by global greenhouse gas emissions that are 40% to 70% lower in 2050 than they were in 2010, while greenhouse gas emissions levels need to be near to or below zero in 2100. These figures have been quoted frequently since publication – also by the G7 – in statements supporting the 2 °C target. However, a number of important questions remain unanswered regarding the IPCC assessment of the present literature, particularly in relation to the 40% to 70% range:

1. The emission reduction range is quite wide. Differences in reduction levels within this range may have consequences in relation to longer term reductions and the technologies required. More specifically, the IPCC report indicated that many of the 450 ppm CO_2eq scenarios rely on bio-energy in combination with carbon capture and storage (BECCS) or afforestation/reforestation to provide negative CO_2 emissions in the second half of the century.
2. The range reported in AR5 seems to differ from the range provided for a similar concentration target in AR4. The AR4 report mentions a 50% to 85% reduction rate compared to 2000 for CO_2 only. The IPCC report indicates that the reasons for this difference include the larger number of scenarios assessed in AR5, the incorporation of all greenhouse gases in the AR5 range, and the increased proportion of new scenarios that include net negative CO_2 emission technologies, but it does not specify the contribution made by these factors.
3. Finally, the IPCC provides very little information for more stringent targets than 2 °C, as relevant literature on this topic was still scarce. However, given the current evaluation of the 2 °C target and the possibility of changing the target to 1.5 °C, it would be interesting to examine what effect more stringent climate targets would have on the results.

The overall goal of this report is to provide more insight into the range of global 2050 greenhouse gas emission levels consistent with 1.5 and 2 °C emission pathways. For this, we formulated some specific research questions:

- What are the key characteristics of scenarios consistent with the 2 °C target in terms of CO_2 budgets, timing of emission reductions, technology use, non-CO_2 emissions, as well as afforestation, reforestation and forest management? (Chapter 3).
- What are the challenges with regard to negative CO_2 emissions? (Chapter 4)
- How do assumptions regarding net negative CO_2 emissions and technology availability affect the 2050 emission reduction level needed for the 2 °C scenarios? (Chapter 5)
- How do more ambitious climate targets affect the 2050 emission reduction range? (Chapter 6)

This report has addressed these questions mainly through a review of the IPCC AR5 scenario database. Around 1200 scenarios were collected for AR5 by the author team for Chapter 6 of the IPCC report. The details of this database are discussed in the technical annex to the IPCC report. The same database was used here to answer most of the research questions and we also looked at the current relevant literature on this topic.

2 Main concepts

2.1 Leverage points to respond to climate change

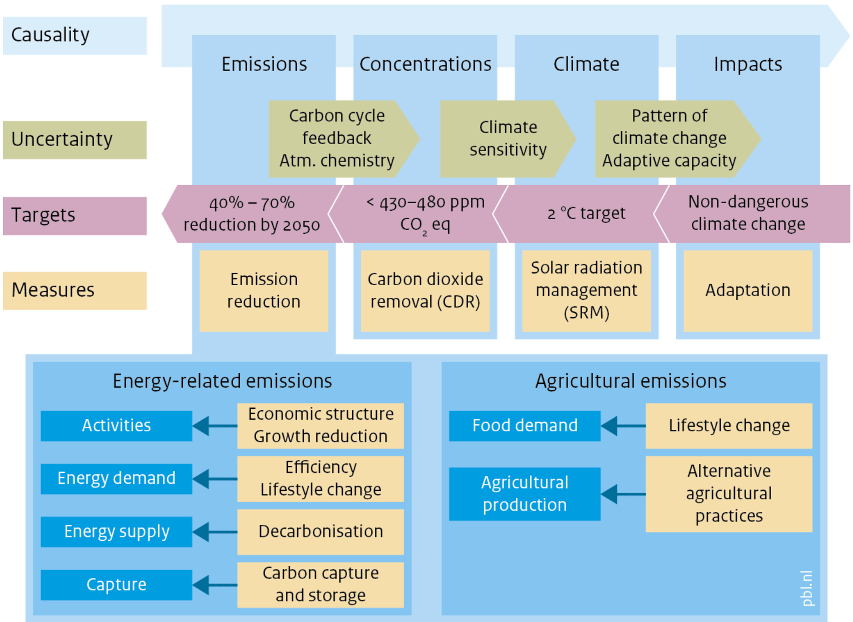
Quantitative scenarios are often used as a means to explore possible pathways for future climate policy. These scenarios are based on models that combine information on projected trends in activity levels in different economic sectors, the anticipated cost of different technologies to supply energy and reduce greenhouse gas emissions, and the expected consequences for climate change (van Vuuren et al., 2014).

These quantitative scenarios have shown that there are various leverage points in the system which can be used to respond to climate change (Figure 2.1). Each of these options is associated with specific costs, benefits and risks. In policy-making a combination can be made on the basis of public preferences. It should be noted that they each clearly have a different potential, and different levels of risks.

- Reducing greenhouse gas emissions (mitigation);
- Removing CO_2 from the atmosphere (carbon dioxide removal, CDR);
- Limiting climate change by breaking the link between greenhouse gas concentrations and warming (solar radiation management, SRM);
- Limiting climate impacts through adaptation measures.

In this report, we will primarily focus on emissions and emission reduction measures.

Figure 2.1
Climate change causality, targets and measures



Source: PBL

Causality, targets and measures of climate change. Based on van Vuuren et al. (2014).

2.2 Metrics of future climate change

While CO_2 contributes most to global warming, other greenhouse gases such as CH_4 and N_2O are important as well (see Section 3.5). To enable comparison of different greenhouse gases in the atmosphere, the contribution of different greenhouse gases is often measured in terms of their CO_2 equivalent (CO_2eq) emissions. CO_2eq emissions are usually calculated by multiplying emissions of a specific gas by its Global Warming Potential (GWP) – a measure of the heat trapped by the gas compared with the amount of heat trapped by CO_2. As different greenhouse gases have different lifetimes in the atmosphere, the GWP values depend on the evaluation period. Typically, 100 years is taken for this.

Similarly to emissions, there is also an interest in summarising the contribution of different greenhouse gases in the atmosphere in terms of an aggregated number. A commonly used metric here is combined radiative forcing, defined as the difference in solar irradiance absorbed by the Earth and the energy radiated back to space. Radiative forcing is expressed as W/m^2. This forcing can also be expressed in terms of CO_2eq concentration levels in the atmosphere measured in parts per million (ppm) CO_2eq (which expresses the equivalent level of CO_2 alone that would produce the same forcing of all the gases combined). This means that the CO_2eq concentration level and CO_2eq emissions are separately defined concepts and are therefore not related to one another.

The impact of changes in radiative forcing levels on climate change is usually expressed in terms of a global mean temperature increase. As the relationship between greenhouse gas forcing and temperature is very uncertain, the projected global mean temperature change must always be expressed in terms of its probability. For instance, based on calculations using the simple climate model MAGICC, keeping the global mean temperature below 2 °C with a more than 66% probability would require greenhouse gas concentrations to stabilise at around 450 ppm CO_2eq (Meinshausen et al., 2006).

It should be noted that the numbers presented in this report refer to total emissions (fossil-fuel combustion, industrial processes and land use), unless specified otherwise.

3 Emission reduction pathways consistent with the 2 °C target

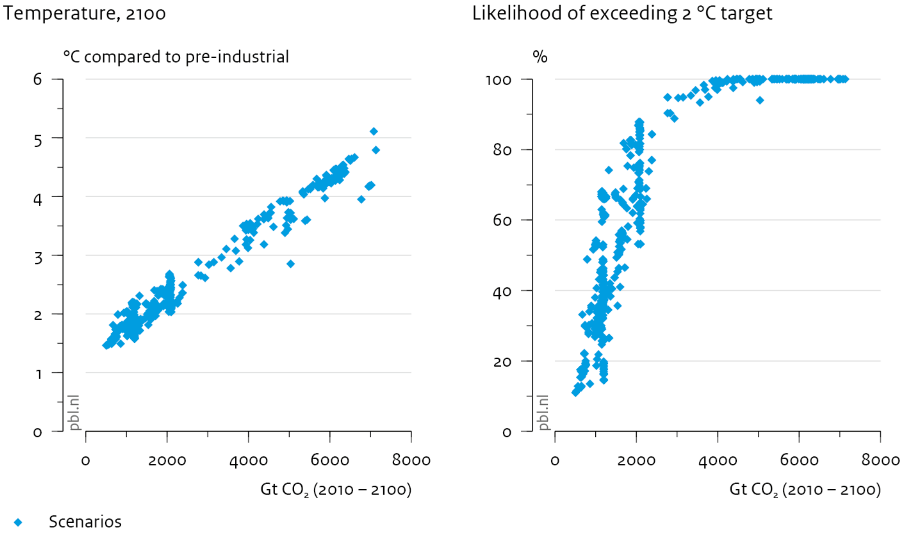
3.1 CO2 budget for meeting the 2 °C target

Integrated assessment models can be used to explore possible emission pathways for different future energy and land-use developments. The same models can also be used to show how specific climate targets and goals can be met. The AR5 Report recently reviewed a large set of emission scenarios published in the scientific literature, subdivided into different categories based on the projected radiative forcing in 2100.

Without additional climate policies, models typically project rapidly increasing emissions of CO_2 and other greenhouse gases over the next few decades, followed by a slower rate of increase after 2050. Such emission pathways typically lead to greenhouse gas concentration levels of 720 to more than 1,000 ppm CO_2eq by the end of the century. These scenarios are associated with an increase in global mean temperature in the order of 3.5–4° C.

In its assessment the IPCC WGI concluded that there is a strong relationship between the long-term climate implications of different scenarios and their cumulative CO_2 emissions, or 'carbon budget'. This is also reflected in the scenario results in WGIII. Figure 3.1 shows the relationship between cumulative CO_2 emissions in the scenarios and climate outcomes. Over the whole range there is a very close relationship between these variables. The right-hand panel shows that to achieve the 2 °C target with a 50% probability, cumulative CO_2 emissions need to be limited to around 1,500 GtCO_2, while to achieve this target with a 66% probability a carbon budget of around 1,000 GtCO_2 would be required, which is consistent with the values given in the IPCC synthesis report.

Figure 3.1
Cumulative CO_2 emissions and temperature increase, 2100



Source: IPCC AR5 database

Relationship between cumulative carbon emissions over the 2010–2100 period and temperature increase compared with the pre-industrial period, and the probability of exceeding the 2 °C target (based on IPCC AR5 database).

3.2 Timing of emission reductions

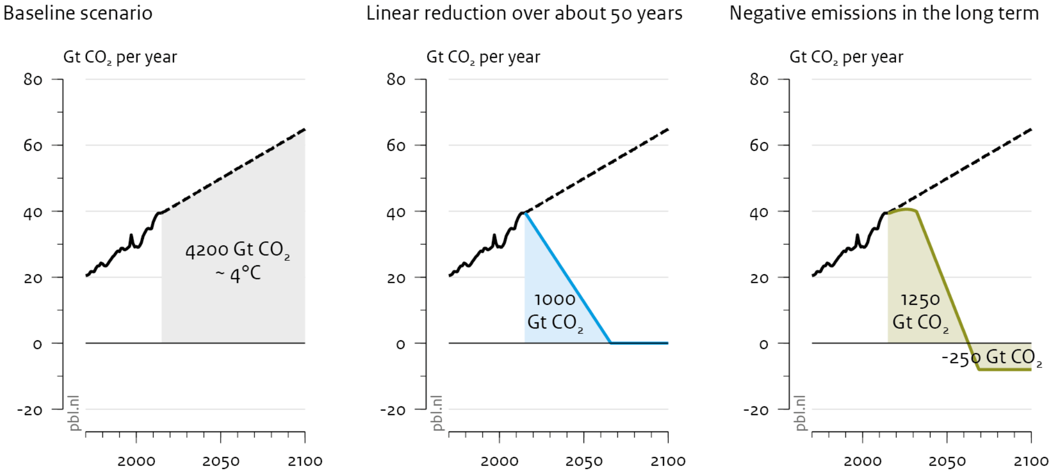
If no global action is taken to curtail CO_2 emissions, the CO_2 budget that corresponds with the 2 °C target will be used up quickly as a result of increasing annual emissions over time, driven by economic and population growth. In fact, at the current rate of emissions, the total budget will be consumed by approximately 2030 (Figures 3.2 and 3.4). In the long-term, scenarios without additional action lead to cumulative emissions of roughly 4,000 $GtCO_2$ up to 2100, corresponding to an expected temperature rise of more than 4 °C (see left panel in Figure 3.2).

The timing of emission reductions in pathways that limit cumulative CO_2 emissions to around 1,000 $GtCO_2$ (from all sources) greatly depends on whether or not it is assumed that net negative CO_2 emissions are possible later in the century. This is depicted in panels b and c in Figure 3.2. Panel b shows a trajectory that corresponds to a maximum 1000 $GtCO_2$, without the use of net negative CO_2 emissions. This implies that emissions need to be zero in about 50 years' time, assuming a linear reduction. As the lifetime of many of the energy technologies we currently employ is about 40 to 50 years, this implies that a large share of new investments in energy supply worldwide must become CO_2-neutral in the next 5 to 10 years. This can be done through a combination of renewable energy, nuclear power, CCS, energy efficiency, bio-energy and lifestyle changes.

Assuming that net negative CO_2 emissions are possible creates some extra flexibility in the time to limit the carbon budget to 1,000 Gt (panel 3 in Figure 3.4). Negative CO_2 emissions would be possible, especially by combining bio-energy with carbon sequestration (BECCS) (Azar et al., 2010) (other options include afforestation/reforestation and direct air capture, i.e. directly removing CO_2 from the atmosphere in combination with storage). However, the use of BECCS would make us dependent on a combination of two controversial technologies; the unproven carbon sequestration method and bio-energy (see also Section 4).

Figure 3.2

Baseline and possible mitigation scenarios to stay within a 2 °C CO_2 budget



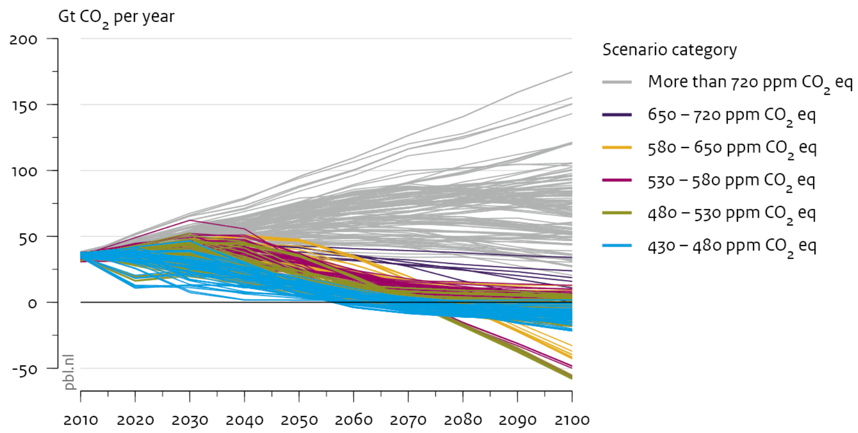
Source: PBL

Stylised emission trajectories to limit cumulative CO_2 emissions to 1,000 $GtCO_2$.

The same dynamics can be observed in the scenarios published in the literature (Figure 3.3). For concentrations of less than 720 ppm CO_2eq, global CO_2 emissions peak somewhere during the 21st century followed by a distinct decline. For more stringent targets of 2 °C with at least 50% probability, concentration levels of 530 ppm CO_2eq or less are needed. This requires an earlier emission peak followed by rapid emission reductions. The vast majority of the scenarios further combine this with net negative CO_2 emissions by the end of the century (similar to panel c in Figure 3.2) in order to reduce somewhat the rapid emission reductions in the first half of the century.

Figure 3.3

CO_2 emissions under various scenario categories

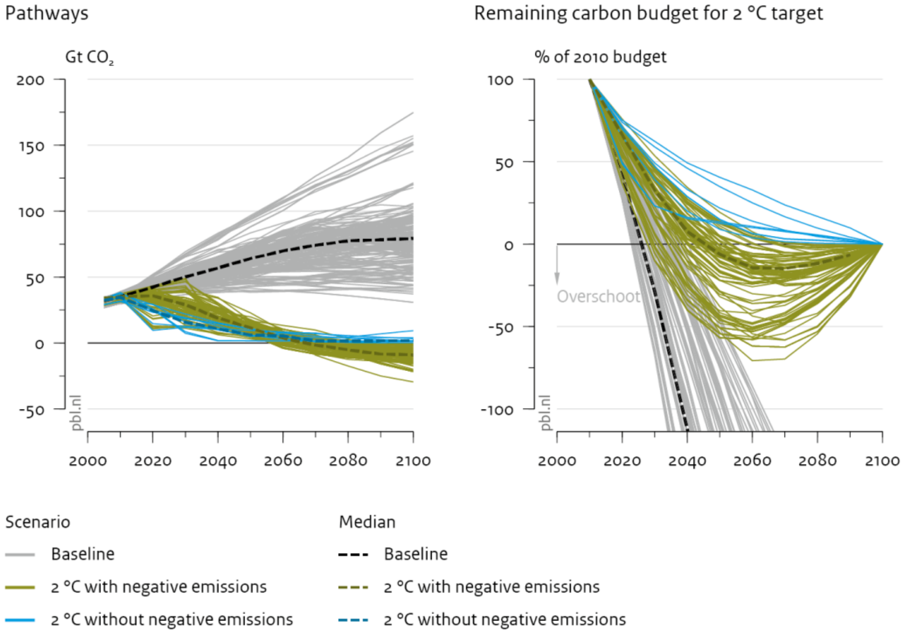


Source: IPCC AR5 database

CO_2 emission profiles over time for different scenario categories.

Figure 3.4 focuses in more detail on those scenarios in AR5 that are consistent with the 2 °C target and the role of net negative CO_2 emissions. The blue lines indicate scenarios that meet the 2 °C target without reducing CO_2 levels below zero, while the scenarios indicated by the green lines depend on net negative CO_2 emissions. The scenarios without net negative CO_2 emissions show more rigorous emission reductions before 2050 to avoid overshooting the original budget. These scenarios also do not rely on net negative-emission technologies (although they might apply some of these technologies to compensate for remaining emissions in other sectors). The right-hand panel in Figure 3.4 clearly shows that scenarios with net negative emissions typically overshoot the carbon budget by 10% to 50%, returning to the original budget in 2100 by relying on net negative CO_2 emissions.

Figure 3.4
CO_2 emission pathways and remaining carbon budget

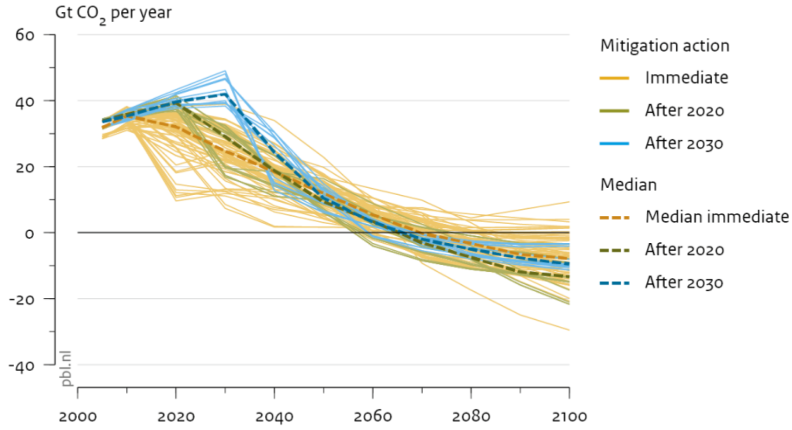


Source: IPCC AR5 database

CO_2 emission pathways (left) and remaining carbon budget (right). The carbon budget is defined as the total allowable cumulative CO_2 emissions in the 430–480 ppm concentration category until 2100.

Delaying global efforts results in higher emission levels in the short run, which will have to be offset by even lower emissions and thus very rapid emission reductions later in the century (Figure 3.5). If climate action is postponed until 2030, about 70% of the overall cumulative budget for 450 ppm CO_2eq (with a likely probability of attaining the 2 °C target) will have already been released into the atmosphere.

Figure 3.5
Effect of delay on CO_2 emissions under 2 °C scenarios



Source: IPCC AR5 database

The effect of delaying mitigation action on emission reduction rates. Based on Riahi et al. (2015)

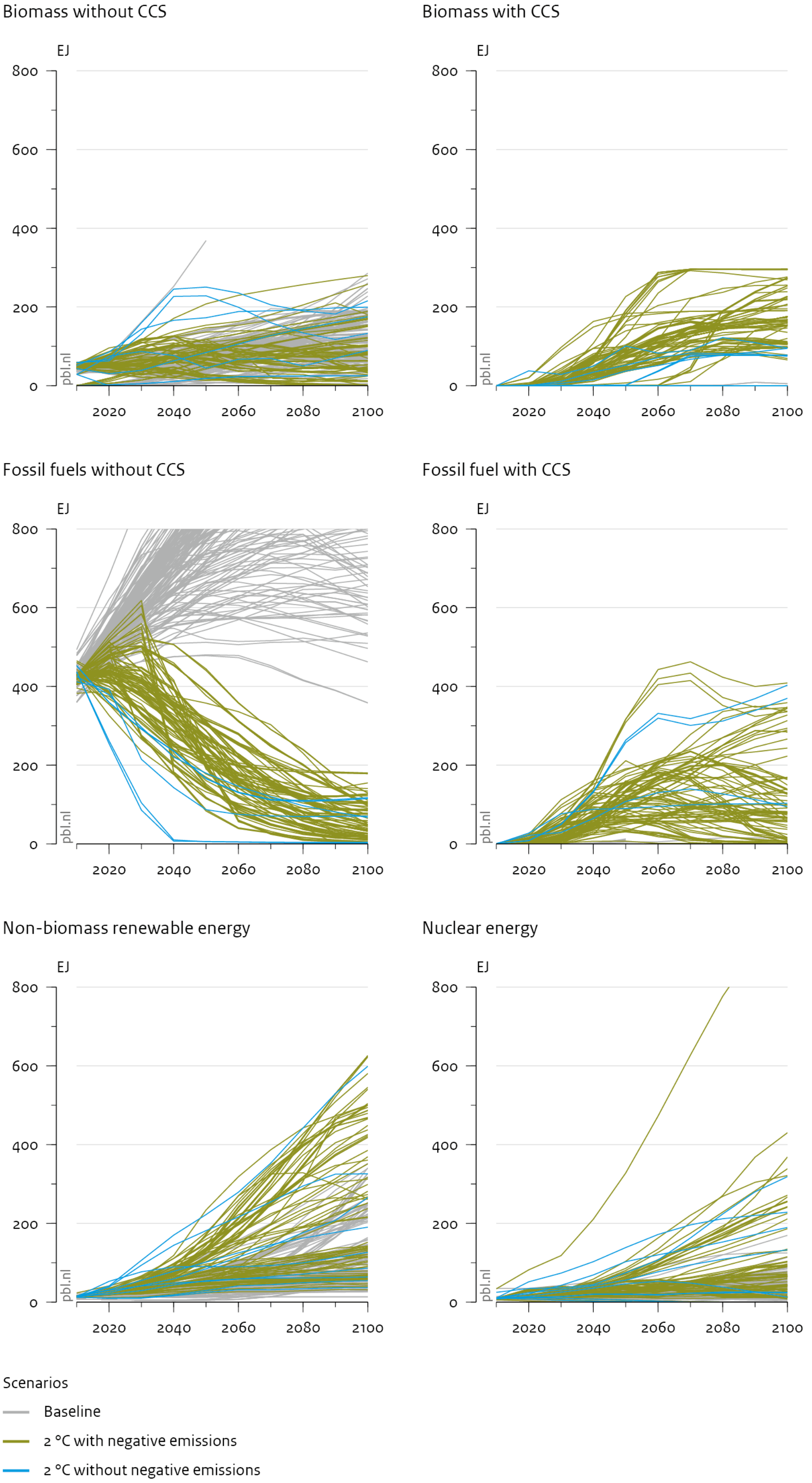
Delaying global action has clearly some advantages in allowing for more time to reach agreement in international negotiation processes, strengthen the initial policies towards low-greenhouse-gas economies in high-income countries and to slowly build up similar policies in low-income countries. However, it also poses a number of challenges:

1. **Reduced flexibility**: Higher short-term emission levels require more rapid system transformation in order to remain on course to meet the 2 °C target. This reduces flexibility and narrows the available policy options.
2. **Lock-in:** Continuing our dependence on a fossil-intensive energy system increases the risk that some of the currently optional technologies, such as the large-scale deployment of biomass or CCS, will become 'mandatory' by 2030 in order to achieve a low stabilisation target.
3. **Increased costs:** Moreover, if it becomes necessary to massively accelerate the system transformation process, this will increase the associated mitigation costs. Negative CO_2 emissions can play a significant role in creating more flexibility and constraining mitigation costs.
4. **Increased climate risks**: Reductions somewhat later in time also imply higher greenhouse gas concentrations. This could also lead to an increased risk of exceeding critical thresholds in the climate system. This risk is likely to be small for a small overshoot given inertia in the climate system which would lead to only 0.1–0.2 °C temperature increase or less. In terms of the rate of temperature change, the impacts can be larger – which could pose challenges for human adaptation (see also Section 2.3 of IPCC's Synthesis Report of the 5th Assessment Report).

3.3 Technology use in scenarios consistent with the 2 °C target

Several models were used to create the 2 °C scenarios in the AR5 database. These models all differed in terms of assumptions regarding, e.g. technological progress, bio-energy availability, CO_2 storage capacity, and the potential for afforestation and reforestation. As a result the technology mix in the 2 °C scenarios also differed widely between models, as indicated in Figure 3.6 which shows the use of different technologies in the baseline and the 2 °C mitigation scenarios, both with and without net negative CO_2 emissions.

Figure 3.6
Primary energy use per technology



Source: IPCC AR5 dataBaseline

Overview of the share of a technology in total primary energy production for all AR5 scenarios consistent with the 430–480 ppm CO_2 concentration level.

The baseline scenarios exhibited substantial use of fossil fuels without CCS. In the 2 °C scenarios this is reduced to nearly zero by the second half of the century, especially in the scenarios that do not have net negative CO_2 emissions. Some mitigation scenarios showed considerable use of fossil fuels with CCS (up to 400 EJ/yr) while no clear relationship with the use of net negative CO_2 emissions can be seen.

The mitigation scenarios show similar deployment levels for nuclear, non-biomass renewable energy and fossil fuels with CCS. While here too no clear relationship can be seen between scenarios with and without net negative CO_2 emission by the end of the century, in the short term the deployment of nuclear and non-biomass renewable energy is greater in scenarios without net negative CO_2 emissions. The use of BECCS is obviously considerably more in the scenarios with rather than without net negative CO_2 emissions. By contrast, the use of bio-energy – certainly in the short term – is much higher in the scenarios without net negative CO_2 emissions (to compensate for the loss of reduction options through BECCS). This means that in many cases the total bio-energy does not differ very much between the scenarios with and without net negative emissions.

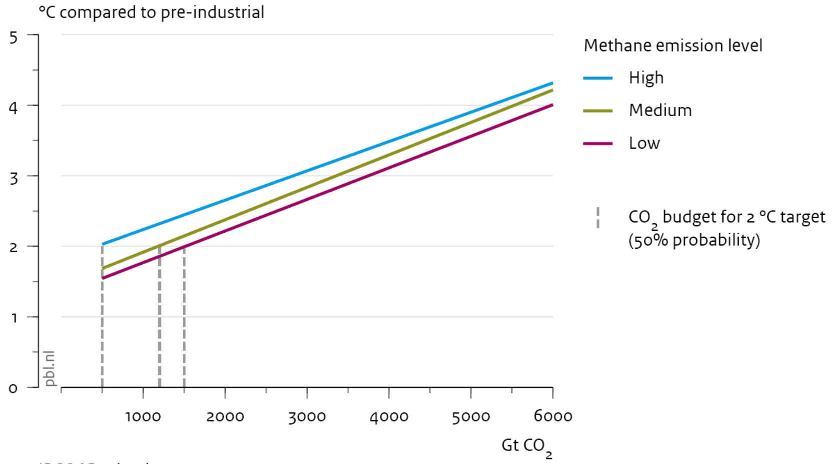
Table 1.1 Overview of the share (in %) of the technologies in total primary energy production for AR5 scenarios consistent with 430–480 ppm CO_2 concentration levels

	2030	2050	2100
	Mean and range (%)		
FULL PORTFOLIO			
Nuclear energy	4 (3-7)	6 (3-9)	11 (2-35)
Biomass with CCS	2 (0-10)	13 (5-22)	24 (10-38)
Biomass without CCS	10 (5-18)	11 (4-16)	11 (0-17)
Fossil without CCS	74 (61-87)	40 (33-55)	8 (3-15)
Fossils with CCS	5 (0-8)	16 (11-21)	15 (5-24)
Non-Biomass Renewable energy	6 (4-12)	13 (6-20)	30 (9-50)
No CCS			
Nuclear energy	7 (1-23)	11 (0-37)	18 (0-52)
Biomass with CCS	0	0	0
Biomass without CCS	21 (0-31)	30 (0-41)	27 (0-37)
Fossil without CCS	56 (47-76)	26 (21-35)	2 (0-4)
Fossils with CCS	0	0	0
Non-Biomass Renewable energy	15 (9-24)	30 (17-44)	51 (22-70)

3.4 Non-CO_2 emissions

The scenarios used in the AR5 Report provide information on both CO_2 emissions and other greenhouse gases, such as CH_4, N_2O and F gases (HFCs, PFCs and SF6). Currently, non-CO_2 greenhouse gases contribute about 20% to 30% to the total Kyoto gas emissions, of which CH_4 (methane) makes the largest contribution. Therefore, non-CO_2 emissions have a considerable impact on climate change as well – thereby influencing the relationship between carbon budget and temperature. This is illustrated in Figure 3.7 which shows how uncertainty about methane emissions affects the carbon budget as captured by the set of scenarios included in the AR5 database. The figure indicates that methane emissions (and policies aimed to reduce them) are important to the carbon budget necessary to be consistent with achieving the 2 °C target: in scenarios with relatively high CH_4 emissions, the carbon budget may be 1,000 $GtCO_2$ lower than in scenarios with relatively low CH_4 emissions (see Figure 3.8 for median values of 2100 CH_4 emissions and the range). It should also be noted that although methane is the most important non-CO_2 greenhouse gas, carbon budgets to a certain degree also depend on other non-CO_2 emission trajectories.

Figure 3.7
Effect of methane level on relation between cumulative CO_2 emissions and temperature increase



Source: IPCC AR5 database

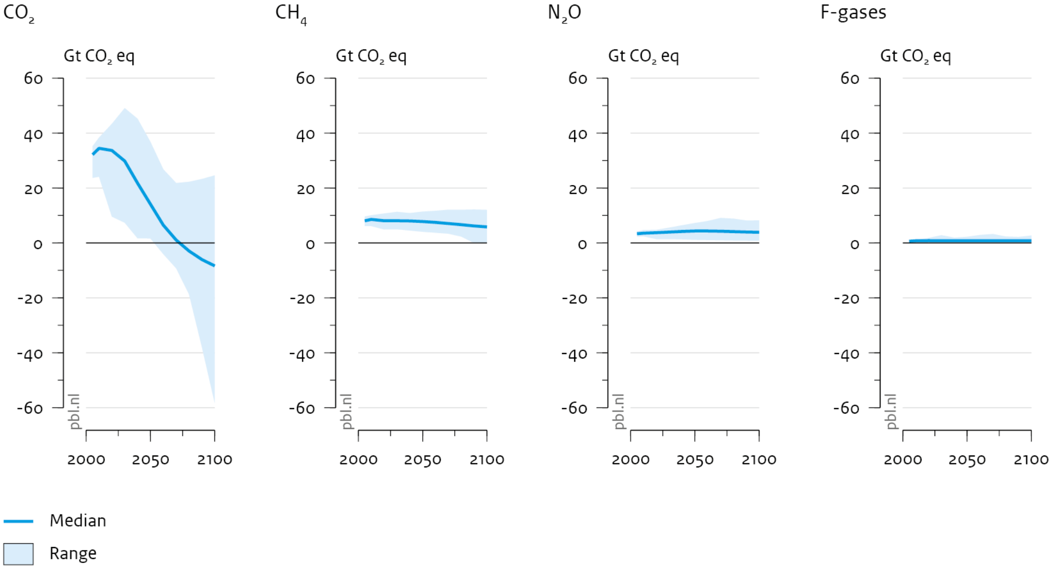
Relationship between cumulative CO_2 emissions and temperature: influence of methane emission level on the size of the carbon budget for the 2 °C target. The uncertainty range represents the outcomes of the different scenarios and models in the AR5 WG3 scenario database, mostly reflecting different assumptions on the reduction potential and costs of non-CO_2 greenhouse gases.

Studies that consider both CO_2 and non-CO_2 mitigation options generally report the greater advantages of so-called multi-gas mitigation strategies, including:

(1) cost reductions compared with CO_2-only strategies, due to relatively cheap abatement options for several non-CO_2 greenhouse gas sources;
(2) more flexibility in abatement options;
(3) more rapid response strategies by focusing on short-lived gases.

However, on a global scale, the emission reduction potential of non-CO_2 gases tends to be more constrained than the potential for CO_2 emission reductions, especially due to limited options for reducing emissions from agriculture (Gernaat et al., 2015). This is illustrated in Figure 3.8.

Figure 3.8
Greenhouse gas emission pathways under mitigation scenarios



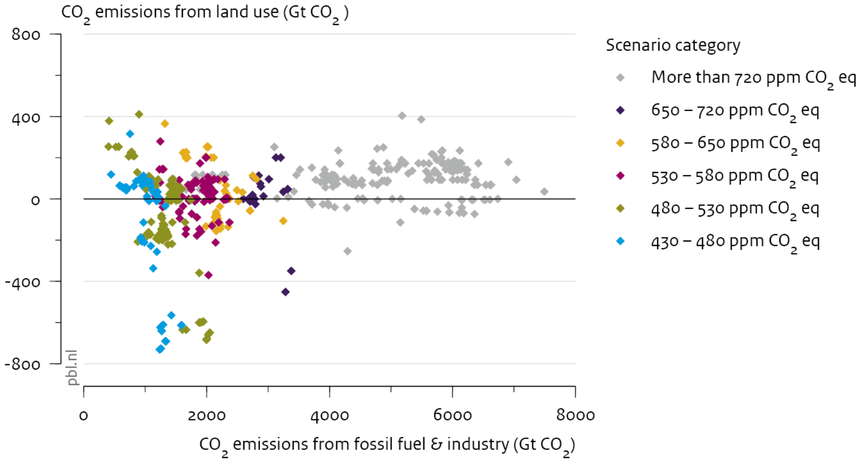
Source: IPCC AR5 database

Overview of 2 °C greenhouse gas trajectories. The bands represent the spread of average model results in 2 °C scenarios for different greenhouse gases and the lines show the mean value of model and scenario results consistent with the 430–480 ppm CO_2 concentration level. The figure shows that, even for stringent scenarios, emissions of CH_4 and N_2O are likely not be reduced to zero by 2100.

3.5 Afforestation, reforestation and forest management

In additional to bio-energy and CCS, (net) afforestation and reforestation can also lead to net negative CO_2 emissions (assuming that deforestation is accounted for). Strengers et al. (2008) reported a mitigation potential from afforestation up to 10 $GtCO_2$/year in the 2010–2050 period under the most optimistic assumptions, but indicated that around 4 $GtCO_2$/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. This is also illustrated by the wide range of outcomes for the contribution of land-use-related CO_2 emissions in the scenarios assessed in AR5 (Figure 3.9). One complicating factor here is that many models do not explicitly look at strategies to reduce agricultural, forestry, and other land use (AFOLU) CO_2 emissions. Hence, the spread in net AFOLU emissions reflects not only real uncertainty, but also simply a different representation between models. As a result, some studies indicate that net AFOLU emissions increase as a result of bio-energy production displacing forests, while others show a decrease in net AFOLU emissions as a result of decreased deforestation, forest protection, or afforestation applied as a mitigation measure.

Figure 3.9
Relation between cumulative CO_2 emissions from energy & industrial sources and land use, per scenario category, 2011 – 2100



Source: Clarke et al. 2014

Cumulative net CO_2 emissions (2011 – 2100) from energy/industry (horizontal axis) and AFOLU emissions (vertical axis). (Clarke et al. (2014, p. 436).

4 Challenges for negative emissions

The difference between the scenarios with and without net negative CO_2 emissions represents a clear policy trade-off: without net negative CO_2 emissions very rapid emission reductions will be needed in the short term; with net negative emissions, emissions could be reduced at a somewhat slower pace but at the expense of relying on a specific mitigation option. Models tend to indicate that too rapid short-term reductions could be expensive compared to the cost of negative emissions in the long term (based on expected technology development rates and assumed discounting rates), and thus favour strategies in which considerable levels of net negative emissions are applied. One of the main reasons for this is that, in the short term, several inertia factors are at play. The typical lifetime of a fossil-fuel-fired power plant, for instance, is around 40 years (Philibert, 2007). Similar lifetimes apply to industrial plant. The lifetime of other technologies, such as road vehicles, is much shorter, and that of the associated infrastructure may also be relevant (e.g. petrol stations, car manufacturing). Other important inertia factors concern changing consumer preferences, international negotiation processes, policy formulation and the maximum deployment rate for new technologies.

The reliance on net negative CO_2 emissions in most scenarios requires a lock-in of specific technologies, including BECCS or rapid afforestation/reforestation. Scenarios included in the lowest category of AR5 (consistent with a probable chance of achieving the 2 °C target) typically include a considerable amount of net negative emissions, up to 10 $GtCO_2$ annually in 2050 (Fuss et al., 2014). Most of this resulting from the use of BECCS. Here, we focus on the feasibility of this option. It should be noted that feasibility logically depends on the feasibility of bio-energy and CCS combined:

- **Availability and use of bio-energy:** several studies have looked at the availability of bio-energy. The range is very uncertain as it depends on various assumptions and criteria with respect to sustainable production of bio-energy. Concerns relate to implications for competing claims on land (e.g. food production, biodiversity), water and maybe even climate impacts. IPCC AR5 provides a range of 100–400 EJ/yr for 2050. Van Vuuren et al. (2010) showed that the sustainable potential in the IMAGE model alone in 2050 could vary between 0 and 200 EJ/year, depending on a range of assumptions regarding land use, sustainability criteria and yields. This value may reach around 250 EJ/year by 2100. Other studies also looked at this potential. Lomax et al. 2015, for instance, concluded that existing estimates of global sustainable biomass resources for the second half of the century range from around 30 EJ/yr to over 600 EJ/yr, depending on assumed trends in diet, crop yields, land use and population (Lomax et al., 2015).

- **Availability and use of CCS:** the availability of CCS is constrained as well. Firstly, the storage capacity for CO_2 is uncertain (see Table 4.1). Geographic uncertainty plays a role in storage capacity estimates along with various concerns about the safety of storing CO_2 in empty fossil-fuel reservoirs and the potential for safe storage in other categories (such as coal beds, saline aquifers or even the ocean). Secondly, public acceptance is another important constraint (Johnsson et al., 2009). From a fully technical perspective, the estimated global storage capacity ranges from 500 to around 100,000 $GtCO_2$, depending on the underlying assumptions. This means that under the most optimistic estimates, storage capacity would not be a limiting factor on using BECCS at global level (although capacity could run out in certain, densely populated, regions such Korea, Japan and India). Under pessimistic assumptions, however, the potential for BECCS could be seriously constrained by storage capacity (technically maybe 10 GtCO_2/year, if it is assumed that BECCS will be available during the second half of the century, but public acceptance could reduce this number to zero). Furthermore, the maximum storage rate and CCS costs could add to the uncertainty.

- **Infrastructural constraints:** The infrastructure associated with a large-scale use of BECCS also will need to be large-scale. This will pose certain challenges, not only in relation to building an infrastructure that is able to collect emissions from biomass and concentrate flows for the use of biomass in power stations worldwide, but also in building an infrastructure of CO_2 pipelines that will transport CO_2 from power stations to storage sites.

Table 4.1: Overview of estimated global storage capacity (Koelbl et al., 2014).

Source	**Total global potential (GtCO_2)**	
	Min	Max
IPCC (2005)	1,678	111,100
Hendriks et al. (2004)	476	5,880
IEAGHG (2011)	4,887	20,946
Dooley et al. (2006)	10,460 (mean)	
IEA (2009)	8,000	15,000

On the basis of the above considerations, BECCS may be regarded as a potential option for the future energy system. Significant challenges remain, however, especially with respect to the impact of land use and the extent to which CO_2 can be stored. In other words, before any decision can be taken on short- and medium-term emission reduction targets now (e.g. on 2050 targets), the potential for net negative emissions and the associated challenges will need to be carefully considered, and a thorough risk assessment carried out.

5 Greenhouse gas emission reductions by 2050 in long-term scenarios

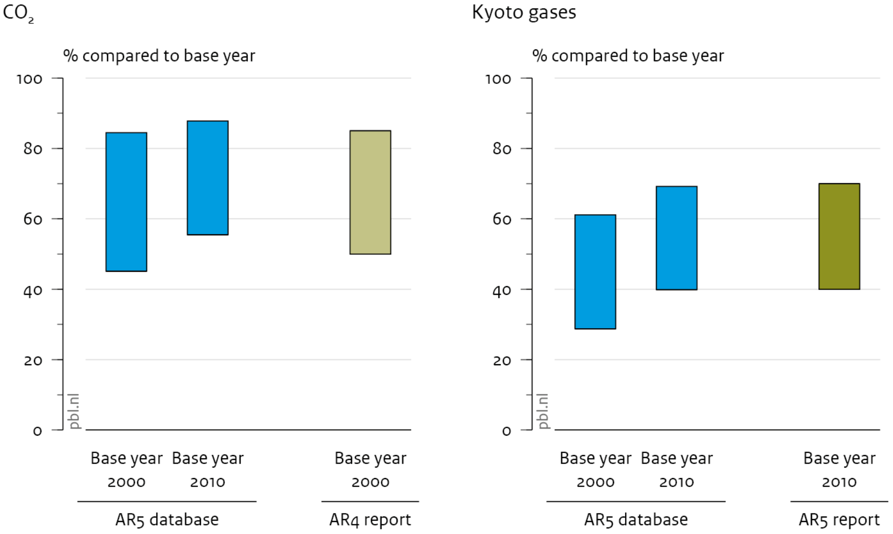
5.1 Comparison between the AR4 and AR5 ranges

Both the fourth (AR4, IPCC, 2007) and fifth (AR5, IPCC, 2014) assessment reports focused on the necessary emission reductions required by 2050 to meet the 2 °C target. However, the manner in which the numerical values of the emission reductions were expressed differs between the two reports. AR4 reports a required *CO_2* emission reduction compared to the *2000* level, while AR5 reports a required *greenhouse gas* emission reduction compared to the *2010* level. While the reported reduction range in AR4 was a 50% to 85% reduction in CO_2 compared to 2000, in AR5 the corresponding range is 40% to 70% for CO_2-equivalent emissions compared to 2020. In other words, the AR5 range seems slightly less stringent. However the following factors need to be taken into account:

- **CO_2 versus all greenhouse gases:** the focus in AR5 shifted from CO_2 to all Kyoto greenhouse gases (GHG). This shift leads to somewhat lower reduction rates by 2050. This is because the potential to reduce CO_2 emissions is assumed to be greater than for non-CO_2 greenhouse gases (see Figure 5.1).
- **Base year**: AR5 reports emission reductions relative to 2010, while 2000 is taken as the base year in AR4. As emissions increased from 2000 to 2010, translating the AR5 range (40%–70%) relative to 2000 levels leads to lower reductions (25%–50%).
- **Number of scenarios**: the number of scenarios significantly increased. AR5 includes 114 scenarios with a likely chance of achieving the 2 °C target, while AR4 included only 6 (the latter is thus more biased by particular models).
- **Policies included**: the scenario analysis in AR5 also included studies that assumed delayed climate action and the restricted availability of certain technologies. This resulted in different reduction levels for 2050 (see Section 5.2).
- **Studied range of results (percentiles):** AR4 concentrated on the 15th–85th percentile whereas AR5 considers the 10th–90th percentile of the scenario results.

Figure 5.1 shows that the difference in the range can essentially be explained by changing only the first two factors (type of gas and base year).

Figure 5.1
Emission reduction compared to base year, 2015



Source: IPCC AR5 database; IPCC AR 5 report; IPCC AR4 report

CO_2 emission reductions (left) and total Kyoto gas emission reductions (right) by 2050 with 2000 and 2010 as base years, as included in the AR5 database. The green bars represents the emission reduction rate as reported in either AR4 (left, for CO_2 emissions only) or AR5 (right, for CO_2eq emissions).
To harmonise AR4 and AR5 we used the 85th percentile value of the 'overshoot < 0.4 W/m^2' subcategory and the 15th percentile value of the 'overshoot > 0.4 W/m^2' subcategory. EDGAR was used to scale AR5 data back to representative 2000 values. (IPCC AR5 emission database.)

5.2 Impact of technology availability and timing

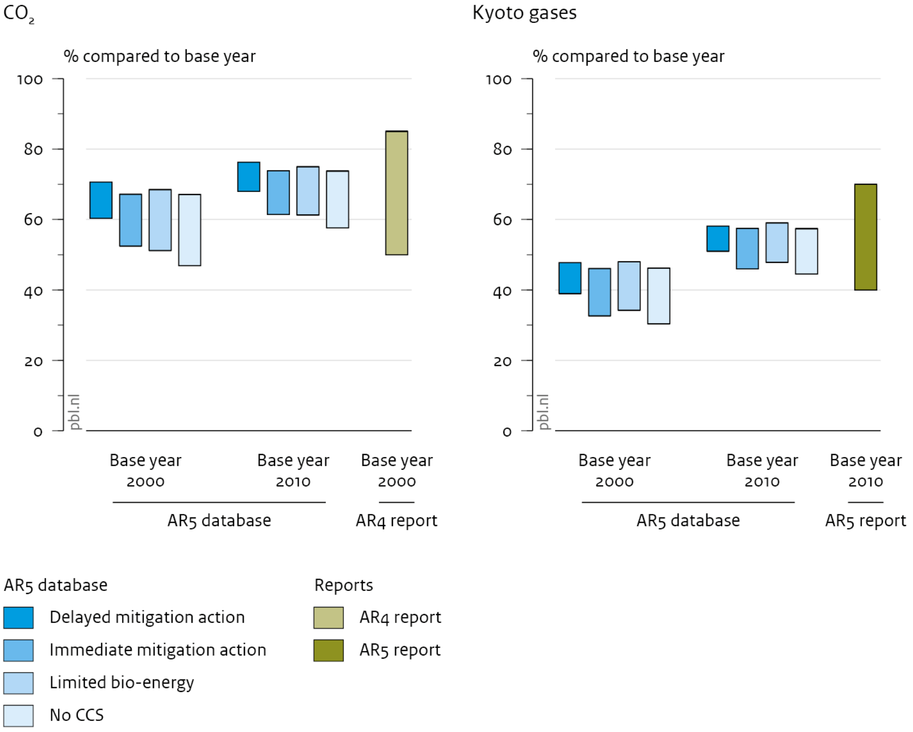
Many 2 °C scenarios have been published since AR4. These scenarios looked, among other things, at the impact of timing and the technology portfolio. Figure 5.2 shows the effects of different assumptions regarding technology and timing on 2050 emission reductions. The following categories were identified:

- The *Immediate* category consists of scenarios with immediate global mitigation action and a full range of technological solutions. These scenarios show a wide range of required emission reductions resulting from differences in model assumptions about technological developments and the availability of carbon removal technologies.
- In the *Delay* category it is assumed that only the policies in the so-called pledges in the period 2020/2030 will be implemented. The scenario assumes the implementation of low-cost mitigation efforts globally to 2020 or 2030. This leads to higher CO_2 emission reductions by 2050 on average (as emissions in the subsequent period have to be compensated for), but this finding is not robust as there is still a large degree of overlap in the uncertainty ranges. The effect on total greenhouse gas emissions is less; probably because the maximum potential for non-CO_2 emissions is more constrained (both the *Immediate* and *Delay* category simply reduce maximum emissions).
- When negative CO_2 emissions are more difficult or even impossible to achieve (*No CCS* and *Limited Bio*), there is a slightly greater focus on reducing non-CO_2 emissions.

- All scenarios with limited technologies show a wider range of mitigation levels for the full greenhouse gas category than for CO_2 emissions only.

The number of scenarios is also given in Figure 5.2. This shows that under restricted technology availability a much smaller number of scenarios achieve the 2 °C target compared to scenarios with a full technology portfolio. Especially when limiting technologies that enable negative emissions are limited or not available, it becomes increasingly difficult for models to provide a feasible trajectory.

Figure 5.2
Emission reduction compared to base year, per scenario type



Source: IPCC AR5 database; IPCC AR 5 report; IPCC AR4 report

CO_2 emission reductions (left) and CO_2eq emission reductions (right) by 2050 for different types of scenarios from the AR5 database. Delayed represents scenarios that do not engage in global mitigation policies before 2020 or 2030. Immediate represents scenarios that engage in immediate global mitigation action.

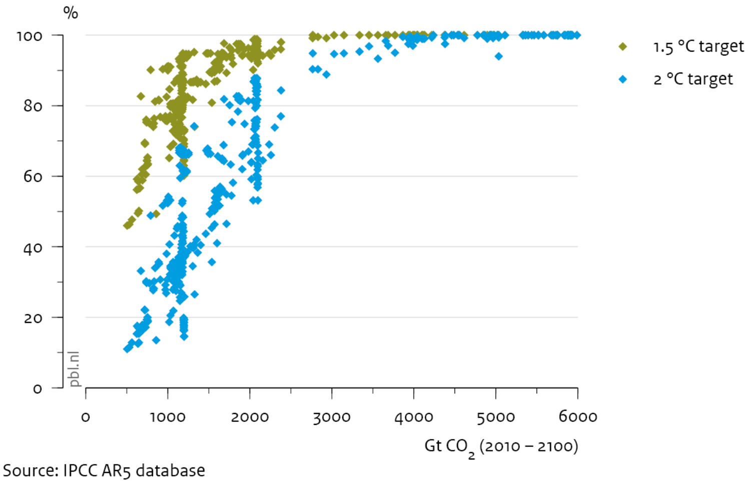
Box 5.1: Derived regional and national targets

The discussion on regional or national targets is even more complicated than on global targets, as these targets not only rely on biophysical, technical and economic considerations, but also on normative choices about the distribution of costs (see also Section 6.3.6.6 of the Working Group 3 contribution to IPCC's Fifth Assessment Report). For instance, the often quoted range of 80% to 95% emission reduction for high-income countries based on the Fourth Assessment Report refers to outcomes of studies taking 'fairness principles' into account (numbers refer to the allocation of assigned amounts before trade and, thus, not to domestic reductions). The Fifth Assessment Report shows that current studies based on allocation principles nevertheless result in similar outcomes. Clearly, emission reductions in the AR5 scenario database cannot be directly compared with such numbers, as the former show the results of cost-optimal emission reduction strategies. In general, also for targets at scales other than the global scale, decisions will need to be made regarding future use of net negative-emission strategies.

6 Implications of limiting temperature change to 1.5 °C

This report focuses on scenarios with a likely chance of meeting the 2 °C target. During UNFCCC negotiations more stringent targets have been discussed that could further limit the risks of dangerous climate change. The carbon budget for targets such as 1.5 °C (with a likely probability) is much lower. For example, the carbon budget for achieving the target with a 50% probability is reduced from around 1250–1500 $GtCO_2$ to less than 500 $GtCO_2$. Similarly, for a given carbon budget of around 1000 $GtCO_2$, the probability of exceeding 1.5 °C is about 50% points higher than the probability of exceeding 2 °C (Figure 6.1). In this context it should be noted that the current temperature increase is already well above 1.0 °C and given the inertia in both the economic and climate systems, it will only be possible to achieve the 1.5 °C target with a temporary overshoot of the emission budget.

Figure 6.1
Cumulative CO_2 emissions and likelihood of exceeding climate target



Source: IPCC AR5 database

Probability of exceeding 1.5 °C and 2 °C as a function of the carbon budget.

Prior to the AR5 assessment, only a small number of studies explored scenarios that are more likely to return the change in temperature to below 1.5 °C by 2100, relative to pre-industrial levels. These scenarios have not been included in the AR5 scenario database but Clarke et al. (2014, p. 441) nevertheless noted that the few studies that have assessed scenarios with a more than 66% probability of remaining below 1.5 °C are characterised by:

- Cumulative CO_2 emissions ranging between 680–800 $GtCO_2$ from 2011 to 2050 and between 90–310 $GtCO_2$ from 2011 to 2100;
- Global CO_2eq emissions by 2050 between 70% and 95% below 2010 emissions, and between 110% and 120% below 2010 emissions in 2100.

Achieving such reductions would require even more immediate mitigation action than for 2 °C, rapid scaling up of the full portfolio of mitigation technologies and development, following a low-energy-demand trajectory. Furthermore, as 1.5 °C scenarios have a lower carbon budget over the 2011–2100 period than over the 2011–2050 period, there is a greater dependency on carbon removal technologies over the second half of the century than there is for 2 °C scenarios.
Rogelj et al. (2015) obtained similar results and noted that 1.5 °C scenarios require net negative CO_2 emissions by mid-century, which is about 10–20 years earlier than most 2 °C scenarios. Moreover, 1.5 °C scenarios show higher mitigation rates in the short term and are therefore associated with higher near-term costs. Table 5.1 summarises some of the requirements for 1.5 °C scenarios based on the few studies that have appeared so far.

Table 5.1: Overview of insights related to long-term climate targets and short-term implications.

	AR5	**Prior to AR5**	**After AR5**
Temperature (°C)	2.0	1.5	1.5
CO_2 concentration (ppm)	430–480	≤ 430	420–440
Carbon budget 2011–2050 ($GtCO_2$)	550–1300	680–800	680–895
Carbon budget 2011–2100 ($GtCO_2$)	630–1180	90–310	200–415
Reference	Clarke et al. (2014, p. 431)	Clarke et al. (2014, p. 441)	Rogelj et al. (2015)

References

Azar C, Lindgren K, Obersteiner M, Riahi K, Van Vuuren DP, Den Elzen KMGJ, Möllersten K and Larson ED. (2010). The feasibility of low CO_2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). Climatic Change 100, 195–202.

Clarke L, Jiang K, Akimoto K, Babiker M, Blanford G, Fisher-Vanden K, Hourcade J-C, Krey V, Kriegler E, Löschel A, McCollum D, Paltsev S, Rose S, Shukla PR, Tavoni M, Van der Zwaan BCC and Van Vuuren DP. (2014). Assessing Transformation Pathways, in: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., Stechow, C.v., Zwickel, T., Minx, J.C. (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge (UK) and New York, NY.

Dooley JJ, Dahowski RT, Davidson CL, Wise MA, Gupta N, Kim SH. et al. (2006). Carbon dioxide capture and geological storage - A core element of a global energy technology strategy to address climate change, College Park, USA: Battelle, Joint Global Change Research Institute

Fuss S, Canadell JG, Peters GP, Tavoni M, Andrew RM, Ciais P, Jackson RB, Jones CD, Kraxner F, Nakicenovic N, Le Quéré C, Raupach MR, Sharifi A, Smith P and Yamagata Y. (2014). COMMENTARY: Betting on negative emissions. Nature Climate Change 4, 850–853.

Gernaat DEHJ, Calvin K, Lucas PL, Luderer G, Otto SAC, Rao S, Strefler J and Van Vuuren DP. (2015). Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. Global Environmental Change 33, 142–153.

Hendriks C, Graus W and Van Bergen F. (2004). Global Carbon Dioxide Storage - Potential and Costs. EEP-02001. PBL Netherlands Environmental Assessment Agency, The Hague/Bilthoven.

IEA (2009). Technology roadmap - carbon capture and storage. IEA / OECD, Paris.

IEAGHG (2011). Potential for Biomass and Carbon Dioxide Capture and Storage. International Energy Agency Greenhouse Gas Research & Development Programme, Paris.

IPCC (2005). Special Report on CO_2 capture and storage. Cambridge University Press, Cambridge.

IPCC (2007). Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, in: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.). Cambridge University Press, Cambridge (UK) and New York, NY.

IPCC (2014). Climate Change 2014. Mitigation of Climate Change Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, in: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., Stechow, C.v., Zwickel, T., Minx, J.C. (Eds.). Cambridge University Press, Cambridge (UK) and New York, NY.

Johnsson F, Reiner D, Itaoka K and Herzog H. (2009). Stakeholder attitudes on carbon capture and storage - An international comparison, Energy Procedia, 1 ed, pp. 4819–4826.

Koelbl BS, Van den Broek MA, Van Ruijven BJ, Faaij APC and Van Vuuren DP. (2014). Uncertainty in the deployment of Carbon Capture and Storage (CCS): A sensitivity analysis to techno-economic parameter uncertainty. International Journal of Greenhouse Gas Control 27, 81–102.

Lomax G, Lenton TM, Adeosun A and Workman M. (2015). Investing in negative emissions. Nature Climate Change 5, 498–500.

Meinshausen M, Hare B, Wigley TML, Van Vuuren D, Den Elzen MGJ and Swart R. (2006). Multi-gas emissions pathways to meet climate targets. Climatic Change 75, 151–194.

Philibert C. (2007). Technology penetration and capital stock turnover: Lessons from IEA scenario analysis. IEA, Paris.

Riahi K, Kriegler E, Johnson N, Bertram C, Den Elzen M, Eom J, Schaeffer M, Edmonds J, Isaac M, Krey V, Longden T, Luderer G, Méjean A, McCollum DL, Mima S, Turton H, Van

Vuuren DP, Wada K, Bosetti V, Capros P, Criqui P, Hamdi-Cherif M, Kainuma M and Edenhofer O. (2015). Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technological Forecasting and Social Change 90, 8–23.
Rogelj J, Luderer G, Pietzcker RC, Kriegler E, Schaeffer M, Krey V and Riahi K. (2015). Energy system transformations for limiting end-of-century warming to below 1.5 °C. Nature Climate Change 5, 519–527.
Strengers BJ, Van Minnen J and Eickhout B. (2008). The role of carbon plantations in mitigating climate change: potentials and costs. Climatic Change 88, 343-–66.
Van Vuuren D, Den Elzen M, Hof A, Roelfsema M, Lucas P, Van Sluisveld M, Gernaat D, Otto S, Van den Berg M, Harmsen M, Schaeffer M and Admiraal A. (2014). Long-term climate policy targets and implications for 2030. PBL Netherlands Environmental Assessment Agency, The Hague.