CHAPTER 2:

What emission levels will comply with temperature limits?

Lead authors: Joeri Rogelj (ETH Zurich / International Institute for Applied Systems Analysis), David McCollum (International Institute for Applied Systems Analysis), Steven Smith (Pacific Northwest National Laboratory)

Contributing authors: Katherine Calvin (Pacific Northwest National Laboratory), Leon Clarke (Pacific Northwest National Laboratory), Monica Crippa (European Commission's Joint Research Centre), Amit Garg (Indian Institute of Management Ahmedabad), Kejun Jiang (Energy Research Institute), Volker Krey (International Institute for Applied Systems Analysis), Jason Lowe (Hadley Centre), Greet Maenhout (European Commission's Joint Research Centre), Keywan Riahi (International Institute for Applied Systems Analysis), Michiel Schaeffer (Climate Analytics), Detlef van Vuuren (PBL Netherlands), Chen Wenying (Tsinghua University)

Over the past few years rapid progress has been made in understanding the impacts of greenhouse gas emissions on global warming. This understanding has also made it possible to better estimate the levels of global emissions consistent with global temperature increase limits, such as 1.5 °C and 2 °C.

This chapter first reviews estimates of recent global emission levels and trends; then examines business-as-usual emission levels that would theoretically be reached if no further action were taken to reduce emissions. Finally, it presents the levels of emissions that are consistent with limits to global temperature increases.

2.1 Current global emission levels

Different data sources give different estimates of global greenhouse gas emissions for 2010 (JRC/PBL, 2012; Blanco *et al.* 2014). The IPCC's AR5 gives a median estimate of 49 gigatonnes of carbon dioxide equivalent (Gt CO_2e; 49±4.5 range, with a 5–95 per cent confidence interval)[1]. A recent update of trends in global emission levels (Figure 2.1) gives a median estimate of 51 Gt CO_2e[2]. In this report (specifically, in Chapters 2 and 3) the AR5 value of 49 Gt CO_2e is used.

Figure 2.1 shows emission levels by major economic groupings for the period 1970–2012. Note that, due to different methodologies and data sources, these values may differ from data derived from national inventory submissions and communications. The general regional trends over recent years were described in last year's report. For 2010–2012, these preliminary estimates indicate that global emissions grew by an average of 3 per cent per year, to 53 and 54 Gt CO_2e in 2011 and 2012, respectively (JRC/PBL, 2012; Olivier *et al.*, 2013; Appendix 2-A). Trends varied from an increase of 6 per cent in the G20 countries that are not members of the Organization for Economic Co-operation and Development (OECD), to a decline of 1 and 2 per cent, respectively, in OECD Europe and OECD North America. Over the last decade, per person emissions also increased in non-OECD G20 countries and decreased in OECD Europe and OECD North America.

[1] For consistency with reporting practices of the UNFCCC and data from the scientific literature, estimates of different greenhouse gas emissions in this report are weighted using Global Warming Potentials (GWPs) from the IPCC Second Assessment Report (Schimel *et al.*, 1996). GWPs have been regularly updated in successive IPCC assessment reports and in the scientific literature.

[2] Updated greenhouse gas emissions estimates as shown in Figure 2.1, based on Olivier *et al.* (2013), JRC/PBL (2012) as described in Appendix 2-A.

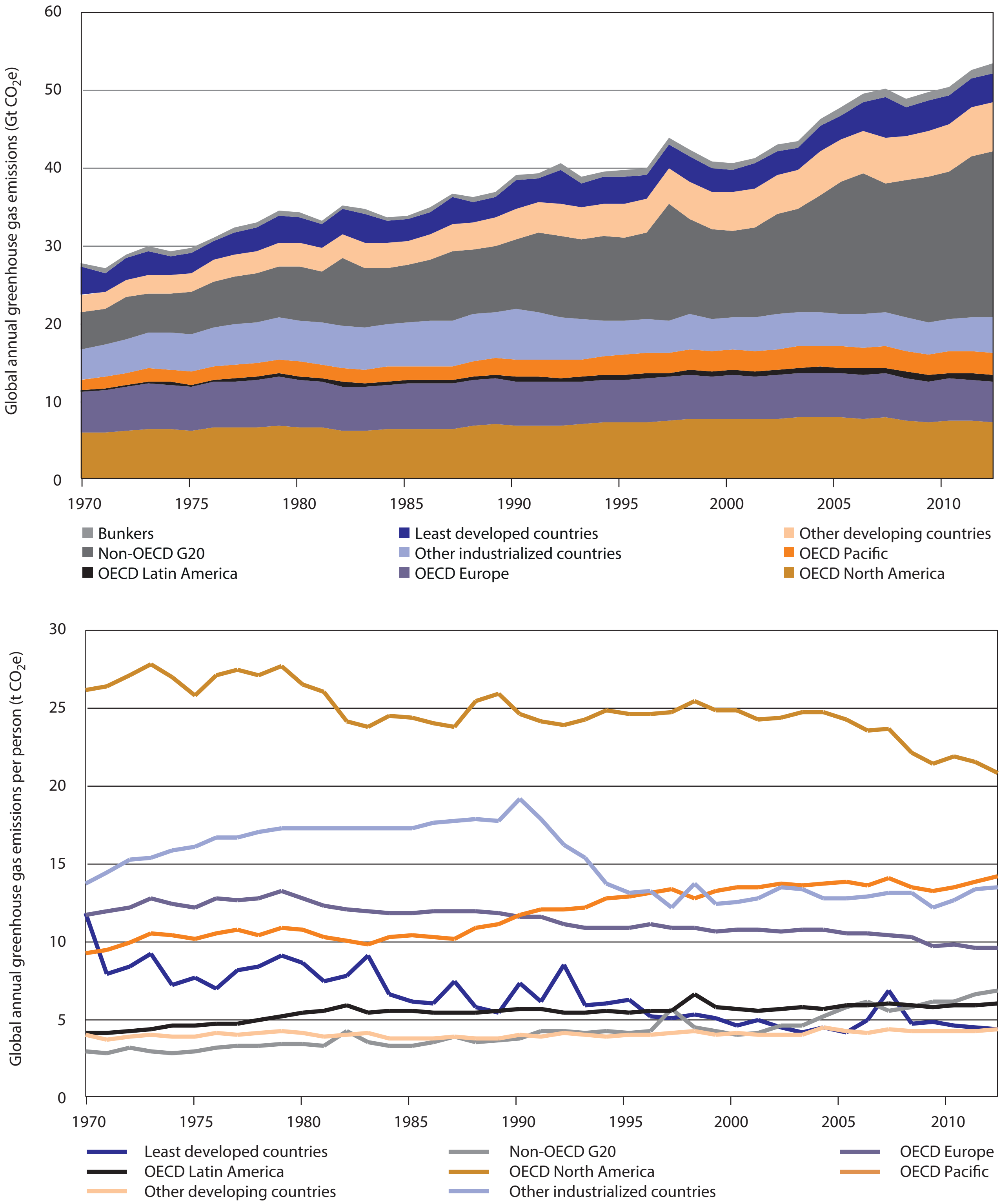

Figure 2.1: Trend in global greenhouse gas emissions 1970-2012 by major economic grouping. Total emissions (top) and per person emissions (bottom).

Notes: Data refer to the sum of emissions of all greenhouse gases listed in the Kyoto Protocol (see Footnote 6 for a listing of these gases). Note that emissions for 2011 and 2012 were extrapolated as described in Appendix 2-A. Data are plotted using global warming potential values from IPCC Second Assessment Report.

Sources: EDGAR 4.3 (JRC/PBL 2014) and GFED land-use emissions as used in AR5.

Carbon dioxide from fossil fuel combustion and cement production is the largest contributor to total greenhouse gas emissions. These emissions grew by about 2.4 per cent per year averaged over 2011 and 2012, and by 2.0 per cent in 2013[3]. This represents a slowing of the 2.7 per cent per year rate of growth experienced over the preceding decade. At the global level, these emissions are fairly well estimated, within a range of ±8 per cent (5–95 per cent confidence interval; Andres *et al.*, 2012). Cumulative carbon dioxide emissions are also a useful indicator of climate impact and the most recent trends, to 2010, are reviewed in AR5 (Blanco *et al.*, 2014).

Methane is the second largest greenhouse gas, and its apparent importance has increased because estimates of its global warming potential have increased from 21 to 28[4]. Methane's share of total greenhouse gas emissions increases from 16 per cent to 20 per cent if the higher estimate of GWP is used (Edenhofer *et al.*, 2014). The absolute value and trends in methane emissions are more uncertain (around ±20 per cent) than estimates of carbon dioxide emissions from fossil fuel combustion and cement production (Blanco *et al.*, 2014). This uncertainty is apparent in the discrepancy between emission estimates based on emission inventories versus atmospheric measurements. While global (anthropogenic) methane emission levels have been steadily increasing over the last three decades according to global emission inventories, they have been stable ssor decreasing based on an inversion analysis of methane concentration trends in the atmosphere (Kirschke *et al.*, 2013). Since 2006, however, both ways of estimating anthropogenic methane emissions indicate that global emissions have been increasing.

2.2 Business-as-usual emission levels

To track the progress of additional targeted climate policies, it is useful to have a reference point for estimating emission levels in the absence of additional policies. When these reference points are presented over a series of future years, they are called business-as-usual (BaU) scenarios. This part of the report presents BaU scenarios of global greenhouse gas emissions[5] up to 2050.

The BaU scenarios shown here are based on an extrapolation of current economic, social and technological trends. They only take into account climate policies implemented up to around 2005–2010[6] (i.e. recent country pledges and policies are not considered) and therefore serve as a reference point for what would happen to emissions if planned climate mitigation policies were not implemented.

The BaU scenarios presented here draw on a much larger and more diverse ensemble of scenarios than previously available. Since the 2013 report, a number of model inter-comparison projects have reported their findings[7], on which the recently published AR5 drew heavily. In fact, a novel product of the AR5 exercise is an interactive scenario database containing all pathways that were reviewed, both BaU and greenhouse gas mitigation scenarios, including thorough explanations of their scenario designs and policy assumptions[8]. Nearly 1 200 scenarios populate the AR5 Database, and about 250 of these can be

[3] The average of estimates from JRC/PBL (2014) and Le Quéré *et al*. (2014).

[4] This is the 10-year global warming potential (please refer to the glossary for a definition). The earlier estimate of 21 is from Schimel *et al*. (1996) and the new estimate of 28 is from the IPCC AR5 based on new physical science understanding from Myhre *et al*. (2013).

[5] Unless otherwise noted, greenhouse gas emissions or total greenhouse gas emissions refers to the sum of the six greenhouse gases included in the Kyoto Protocol (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6). It includes emissions from fossil fuel combustion in the energy and industry sectors, as well as from land use, land-use change and forestry (LULUCF).

[6] Different models use different base years for their internal calibration.

[7] Examples include AMPERE (Riahi *et al*., 2014; Kriegler *et al*., 2014a), EMF27 (Kriegler *et al*., 2014b), LIMITS (Kriegler *et al*., 2013; Tavoni *et al*., 2013), and RoSE (Luderer *et al*., 2013a).

[8] The IPCC WG III AR5 Scenario Database can be accessed at: https://secure.iiasa.ac.at/web-apps/ene/AR5DB/

considered BaU ones according to the definition applied here[9]. This section of the report focuses on a subset of 191 scenarios, produced by 31 different models that take emissions of all Kyoto gases[10] into account and have full global and sectoral coverage.

According to this large ensemble of scenarios, in the absence of additional policies to reduce greenhouse gases, global emissions are projected to rise to 59 Gt CO_2e per year (range: 57–61 Gt CO_2e/yr)[11] by 2020. They are likely to continue climbing to 87 Gt CO_2e per year (range: 75–92 Gt CO_2e/yr) by 2050, equivalent to a 70 per cent increase relative to 2010 (Figure 2.2). Such steep upward trajectories are consistent with global average temperature levels that are around 4 °C warmer in the year 2100 than the period 1850–1900. The likelihood of staying below 2 °C warming is extremely small in this case (Table 6.3 of IPCC WGIII AR5).

The uncertainty ranges of the BaU emissions projections shown in Figure 2.2 reflect different interpretations of economic, social and technological trends. For example, scenarios that are optimistic about fossils fuels and/or are pessimistic about renewable or nuclear energy tend to have emissions near the top of the range. By contrast, scenarios that assume slower growth of the economy and/or energy demand, relative to economic activity, tend to have emissions at the lower part of the range. Although the differences between scenarios are fairly minor in the short- term (2020), they become more pronounced by 2030.

2.3 Global emission levels linked with global warming limits

2.3.1 Introduction

As noted above, countries have agreed to limit global warming to 2 °C relative to pre-industrial levels, and to consider lowering that limit to 1.5 °C (UNFCCC, 2010). Findings reported here and elsewhere, have made it clear that society must limit emissions if it is to stay within its own global warming limits. This raises some important questions which are dealt with in this section:

- What is the level of cumulative greenhouse gas emissions consistent with limiting warming to below 1.5 °C or 2 °C?
- How can this budget of cumulative emissions be distributed over time? Under these budgetary constraints, when are global carbon dioxide emissions expected to reach zero? And how does this translate into a path for total greenhouse gases over time?
- What are the implications of not increasing climate mitigation efforts significantly beyond their current levels?

To address these and other questions, this section draws on the scenarios compiled by AR5 grouped according to their temperature outcomes (Appendix 2-D)[12].

9 Because the different scenarios have different base year (2010) estimates for emissions (most likely resulting from non-standardized data sources and conversion methodologies across models), the current analysis normalizes all 2010 emissions to the same value. An estimate of 49 Gt CO_2e per year is used for doing this because that was the best available value at the time the models were running scenarios for the IPCC AR5 process. Future emissions growth in each scenario is then indexed to this common base-year value. The emission pathways reported in this section have all been indexed in this way. For the non-indexed emission pathways, including the 2010 ranges, see Appendix 2-B. It should be noted, however, that these adjustments via base-year indexing have only a small effect on the spread of future emissions: a variety of other factors are at play. To be sure, the indexing methodology, as applied here, leads to slight increases in emissions levels in 2020, 2030, 2040 and 2050 relative to the raw scenario data, primarily because the majority of models/scenarios in the IPCC AR5-assessed literature use lower values for 2010 emissions. Note that previous studies of baseline emissions projections, for example Blanford *et al*. (2012), have utilized similar normalizing/indexing methodologies to control for different base-year starting points across models.

10 For list of Kyoto gases, see Footnote 5.

11 Unless otherwise stated, all ranges in this and other sections of the report are expressed as 20^{th}–80^{th} percentiles.

12 The IPCC AR5 Working Group III Contribution grouped scenarios based on their resulting carbon dioxide-equivalent concentrations in 2100. This choice allows for a direct comparison with the four representative concentration pathways (RCPs) that were used by the other working groups of the IPCC AR5. In contrast, the main focus of this report is the temperature outcome of emission scenarios. Therefore, the IPCC scenarios are re-grouped based on their probabilities of limiting warming to below specific temperature levels. Appendix 2-D provides a detailed comparison of the results of this report and the findings of the IPCC AR5.

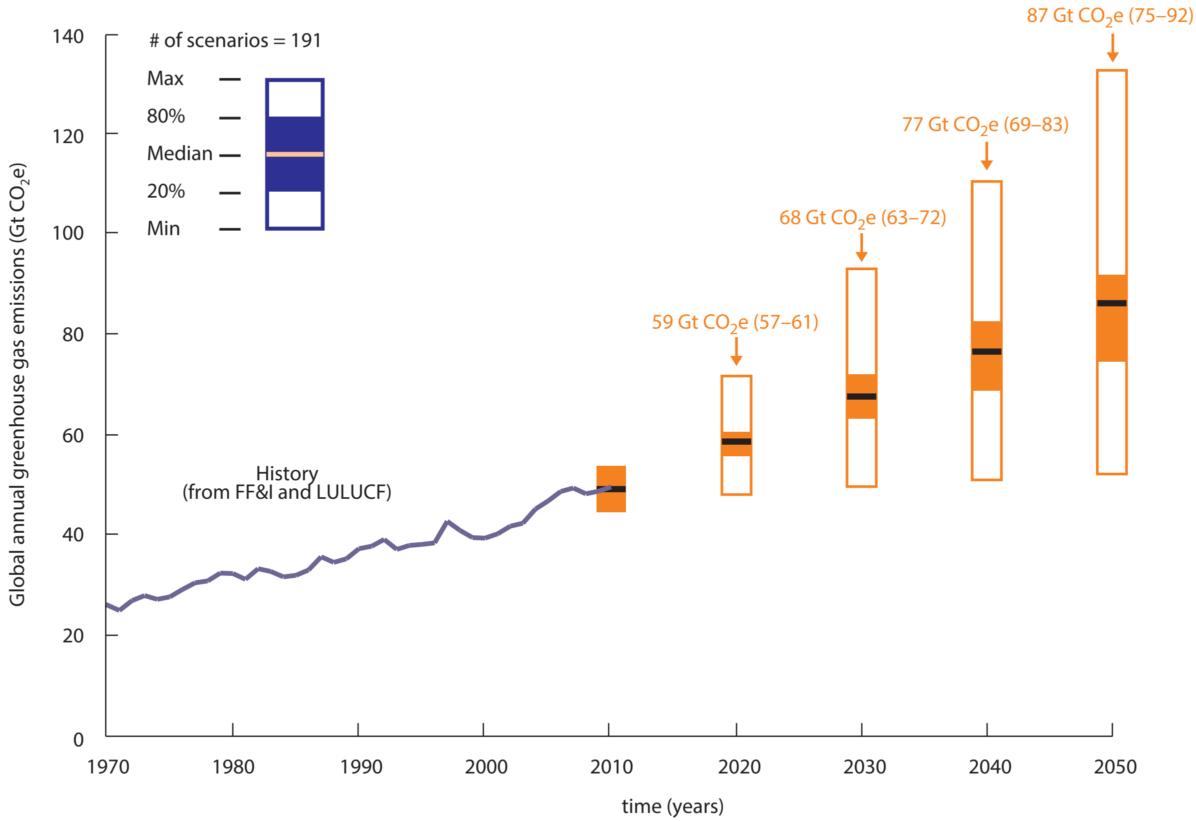

Figure 2.2: Global greenhouse gas emissions in business-as-usual scenarios
Notes: Consistent with IPCC WG III AR5 Chapter 6, carbon dioxide-equivalent emissions are constructed using GWPs over a 100-year time horizon derived from the IPCC Second Assessment Report (see Annex II.9.1 for the GWP values of the different greenhouse gases). Business-as-usual scenarios imply an absence of climate mitigation policies after the 2005–2010 period (such as recent country pledges and policies). Data refer to the sum of emissions of all greenhouse gases listed in the Kyoto Protocol (see Footnote 5 for a listing of these gases.) Historic data are derived from JRC/PBL (2012) and IEA (2012). Future projections come from the IPCC WG III AR5 Scenario Database and are based on estimates from a large number of models. FF&I stands for emissions from fossil fuels combustion in the energy and industry sectors. LULUCF stands for emissions from land use, land-use change and forestry. The range of business-as-usual estimates for 2020 are not the same as in Figure 3.1. This is explained in Footnote 10 in Chapter 3. Scenario results are shown as ranges: 20^{th}–80^{th} percentile spread (colored), full extremes (light box), median in bold.

2.3.2 Geophysical requirements for limiting warming to below 1.5 °C and 2 °C

Working Group I of the IPCC (IPCC, 2013) refined previous estimates of the sensitivity of the climate system to increased greenhouse gas emissions. In doing so it assessed a new metric for expressing this sensitivity – the transient climate response to cumulative carbon emissions (TCRE). Using the TCRE concept, Working Group I showed that global mean temperature increases are almost directly proportional to cumulative carbon dioxide emissions since the pre-industrial period. This leads to the important conclusion that there is a maximum amount of carbon dioxide emissions, or budget that can be discharged to the atmosphere over time if society wishes to stay within a 2 °C or other global warming limit. Both Working Group I and III of AR5 provide carbon dioxide emission budgets in line with various temperature levels (Box 2.1). Because carbon dioxide plays a dominant role in determining long-term warming, we first focus on carbon dioxide emissions and later on total greenhouse gas emissions.

Box 2.1: IPCC AR5 and carbon dioxide emission budgets

Figure B.2.1 (based on Figure SPM.10 of (IPCC, 2013) illustrates how cumulative carbon dioxide emissions are influenced by various factors. If we hypothetically assume that carbon dioxide is the only greenhouse gas affecting global temperature and the response of temperature to cumulative carbon dioxide emissions is constant and well known, then the relationship between global warming and emissions would be represented by a straight line (Panel A). However, since the response is not perfectly known, it has an uncertainty range as illustrated by the grey areas in Panels B, C, and D. Staying below a given temperature limit with a higher probability – for example very likely compared to likely – implies a smaller carbon dioxide budget (Panel B). Furthermore, lowering the temperature limit, say, from 2 °C to 1.5 °C, also implies a smaller budget (panel C). Finally, taking into account the additional global warming caused by non-carbon dioxide emissions at the time when global temperature peaks also reduces the emissions budget, and adds additional uncertainties as expressed by the larger light-orange area in Panel D.

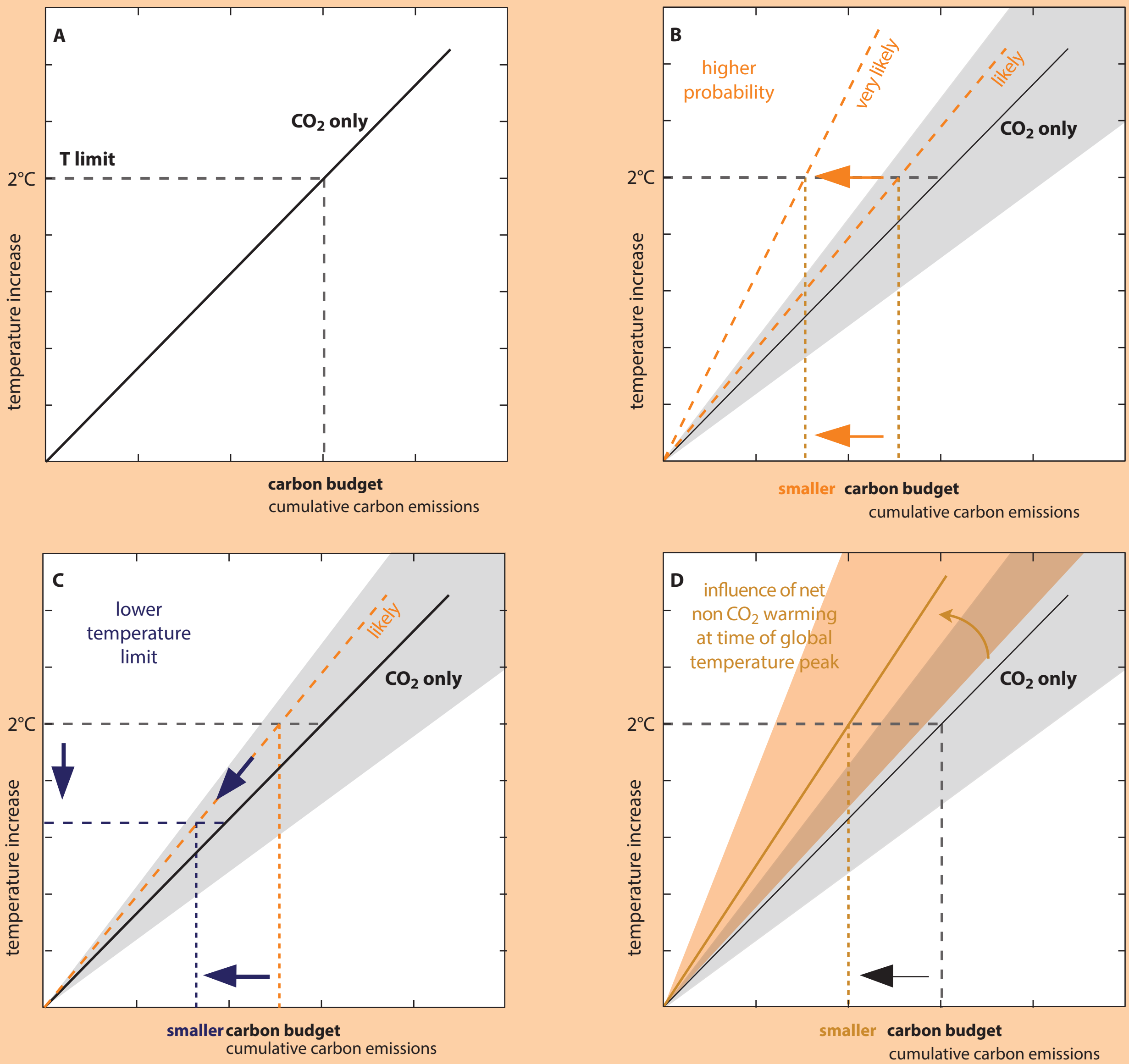

Figure B.2.1: How the transient climate response is influenced by various factors
Source: adapted from Knutti and Rogelj (in review).

As to the size of the carbon dioxide emissions budget, Working Group I of the IPCC indicated – again for the hypothetical case that carbon dioxide would be the only anthropogenic greenhouse gas – that there was a greater than 66 per cent chance that the 2 °C limit could be maintained if cumulative carbon dioxide emissions from around 1860–1880 to some point in the future could be held to 3 670 Gt CO_2 or less. For a greater than 50 per cent chance, this figure is 4 440 Gt CO_2 and for a 33 per cent chance it is 5 760 Gt CO_2. Taking into account non-carbon dioxide emissions, these budgets are smaller.

As a reference point, by year 2011 a total of 1 890 Gt CO_2 (1 630–2 150, 95 per cent confidence range) had already been emitted into the atmosphere by human activities. Hence a large share of the carbon dioxide emissions budget for limiting global warming to 2 °C has already been used up.

IPCC Working Group III also provided information on carbon dioxide emission budgets as part of their analyses of mitigation scenarios (Clarke *et al.*, 2014). For scenarios with a likely chance of staying within the 2 °C limit, they found that cumulative carbon dioxide emissions from 2011 until 2050 are in the range of 550–1 300 Gt CO_2 and from 2011 until 2100 in the range of 630–1 180 Gt CO_2. These figures are broadly consistent with the results from Working Group I. However, the IPCC WGIII assessment, by further exploring the uncertainty in pathways and including a wide range of non-carbon dioxide forcing, has consistently lowered the estimates of carbon dioxide emission budgets in line with 2 °C as compared to those from WGI, which were based on the hypothetical assumption that carbon dioxide is the only anthropogenic greenhouse gas.

Finally, based on multi-model results, the IPCC Synthesis Report stated that likely limiting total human-induced warming (accounting for both CO_2 and other human influences on climate) to less than 2 °C relative to the period 1861–1880 would require total CO_2 emissions from all anthropogenic sources since 1870 to be limited to about 2 900 Gt CO_2 when accounting for non-CO_2 forcing as in the RCP2.6 scenario, with a range of 2 550–3 150 Gt CO_2 arising from variations in non-CO_2 climate drivers. About 1 900 (1 650 to 2 150, 90 per cent range) Gt CO_2 were emitted by 2011, leaving about 1 000 Gt CO_2 to be consistent with the 2°C objective.

Importantly, some non-carbon dioxide greenhouse gases such as methane and tropospheric ozone have a much shorter residence time in the atmosphere than carbon dioxide or nitrous oxide, and are therefore sometimes called short-lived climate pollutants/forcers. Because of their shorter time in the atmosphere, the *annual* emissions of these substances have a bigger impact on temperature than their *cumulative* emissions (Solomon *et al.*, 2010; Smith *et al.*, 2012).

At present, there is still uncertainty around the TCRE estimates which needs to be factored into discussions of future emission pathways. Here this uncertainty is taken into account by grouping scenarios according to their probability to limit warming to below a given temperature limit. A likely chance as used here denotes a greater than 66 per cent probability (Mastrandrea *et al.*, 2010) and a medium chance a probability of 50–66 per cent.

The idea of a carbon dioxide emissions budget implies that annual emissions at some point in time become zero or negative in order to stay within the budget of cumulative emissions (Figure 2.3, right-hand panel, where linearly declining emissions become zero between 2045 and 2075). All in all, this means that annual emissions must ultimately decline, and if they are high now they will have to decline faster later to stay within the budget. Conversely, if annual emissions are lower at the beginning of the budget period, they can be somewhat higher at a later time. This, however, implies a trade-off between earlier and later mitigation costs, and between risks linked to the different strategies (Section 2.3.4).

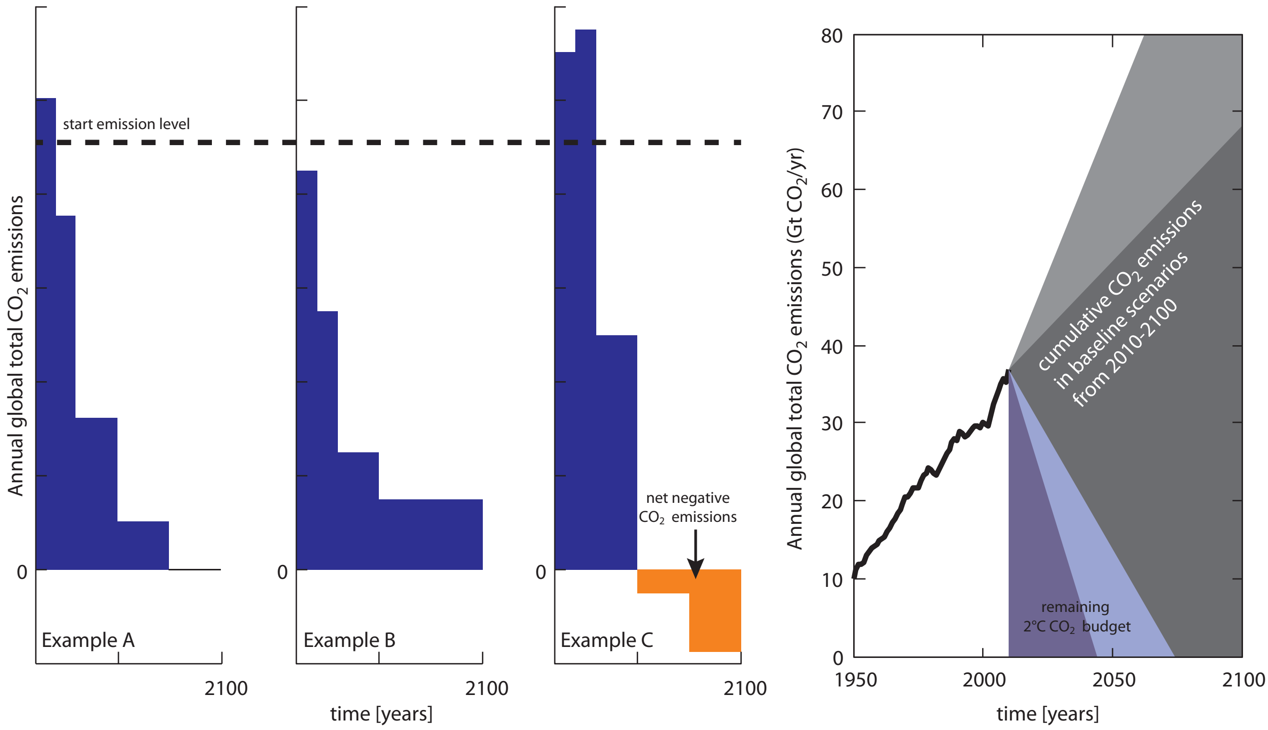

Figure 2.3: Illustration of carbon dioxide emission budgets in line with limiting warming to 2°C

The left hand panels show three conceptual examples that distribute the remaining emissions budget over the 21st century. Note that while Example C *requires* net negative global emissions to stay within the budget, scenarios in the other examples might also make use of negative emissions to a lesser extent if it helps facilitate the required emissions reductions. The examples are explained in the text. The right hand panel shows annual carbon dioxide emissions (black line) over time from Le Quéré *et al.* (2013). The coloured areas under the curves show the cumulative carbon dioxide emissions from 2010 onwards. The purple-coloured area denotes cumulative carbon dioxide emissions with a likely (66 per cent) chance of limiting warming to below 2 °C, including uncertainty. In this report, these cumulative emissions are called the carbon dioxide emissions budget. The grey-coloured area denotes the cumulative carbon dioxide emissions projected under business-as-usual scenarios which assume no climate policies (likewise including uncertainty). The grey area, cumulative emissions under business-as-usual, is clearly larger than the blue area, the carbon dioxide emissions budget for staying within 2 °C. Cumulative emissions are taken from the WGIII assessment of the IPCC AR5 (Clarke *et al.*, 2014).

Over a longer period of time the carbon dioxide emissions budget cannot be exhausted if the goal is to stay within a particular temperature limit. It can be temporarily exhausted but then the accumulation of carbon dioxide in the atmosphere must be compensated by net negative carbon dioxide emissions – emissions that are actively removed from the atmosphere and sequestered. Note, the feasibility of achieving global negative emissions is uncertain and associated with a host of other risks (Fuss *et al.*, 2014).

The left-hand panels of Figure 2.3 illustrate the temporal trade-offs in carbon dioxide emission mitigation. In all three examples emissions decline significantly during the first half of this century, but with important variations. In Example B, action is taken early to reduce emissions, which means that emissions are lower in the first period as compared to Example A. Since the carbon dioxide emissions budget is not used up as quickly in Example B, it has *higher* emissions in the second half of the century than Example A. Meanwhile, in Example C, action is delayed at the beginning of the period and initial emissions are higher than in Examples A or B. To stay within the carbon dioxide emissions budget, Example C requires sharp emission reductions immediately afterwards and net negative emissions in the second half of this century.

These and other trade-offs related to staying within the emissions budget are discussed in Section 2.3.4.

2.3.3 Carbon dioxide emissions budgets, greenhouse gas emissions and temperature limits

We have seen above that it is necessary to stay within a specific carbon dioxide emissions budget to keep warming below 2 °C or some other global warming limit. How then can these budgets be spread out over time? To answer this question, the following sections examine scenarios from integrated assessment models. These models take into account changes in the energy system and other important societal processes, and therefore help identify economically and technologically feasible emission reduction rates and emission pathways. The scenarios are taken from the IPCC WGIII AR5 scenario database[13] (Box 2.2).

As mentioned above, science has convincingly established the proportional relationship between global temperature increases and cumulative carbon dioxide emissions. Hence we first focus on carbon dioxide emissions and then report findings on carbon dioxide plus non-carbon dioxide emissions.

The discussion of carbon dioxide emission budgets is structured according to two dimensions. The first divides scenarios according to the year in which concerted emission reductions[14] begin – either 2010 or 2020:

- **Least-cost 2010 scenarios:** the scenarios in this subset are of the same kind analysed in previous gap reports. These are scenarios with a likely chance of staying within the 2 °C limit and that follow a least-cost emissions pathway with stringent reductions after 2010. A least-cost emission pathway is one that takes advantage of lowest cost options for emission reductions and minimizes total costs of reduction up to 2100.

- **Least-cost 2020 scenarios:** this subset of scenarios also has a likely chance of staying within the 2 °C limit. But they depart from the least-cost 2010 scenarios by assuming that emission reductions are only modest up to 2020, that pledges are fully implemented in 2020, and that a least-cost emissions pathway with rapid reductions is only followed after 2020. These are often called delayed action or later action scenarios because they begin their least-cost pathway in 2020 rather than 2010. (Modest here means that the speed of emission reductions up to 2020 is significantly slower than in the least-cost 2010 scenarios, and emissions actually increase until 2020).

It is important to note that the current pathway of global emissions is so far more consistent with the least-cost 2020 scenarios than the least-cost 2010 scenarios. First of all, emissions in recent years have been higher than in the least-cost 2010 scenarios (Friedlingstein *et al.*, 2014). Second, the least-cost 2020 scenarios seem to be more in accord with current projections of emissions for 2020. Global emissions in 2020 are projected to be 52–54 Gt CO_2e under various pledge cases (Chapter 3). Least- cost 2020 scenarios are close to this range with 50–53 Gt CO_2e in 2020, while least-cost 2010 scenarios are much lower with a range of 41-47 Gt CO_2e in 2020.

The second dimension by which the discussion is structured divides scenarios according to whether or not they rely on net negative carbon dioxide emissions from the energy and industrial sectors in order to stay within the emissions budget. As noted earlier, net negative global emissions are required in some scenarios to compensate for having temporarily exceeded the emissions budget or to facilitate a peak and decline in global

[13] Hosted at the International Institute for Applied Systems Analysis (IIASA) and available at: https://secure.iiasa.ac.at/web-apps/ene/AR5DB/

[14] These are cost optimal scenarios in that they take advantage of the lowest cost mitigation options available.

Box 2.2: Data and methodology

Findings in this report are based on an analysis of emission scenarios available in the IPCC AR5 Working Group III scenario database, hosted at the International Institute for Applied Systems Analysis and available at: https://secure.iiasa.ac.at/web-apps/ene/AR5DB/. We use the original data for carbon dioxide emissions from fossil fuel and industry, total carbon dioxide emissions, and total global greenhouse gas emissions, defined in this report as the gases covered by the Kyoto Protocol. Non-carbon dioxide gases are reported in units of billion tonnes of carbon dioxide equivalent per year (Gt CO_2e/yr), and are computed from the 100-year global warming potentials as specified by UNFCCC (2002).

Not included in the analysis is the recently added greenhouse gas, nitrogen trifluoride (NF_3). Contributions to global temperature increase of the air pollutants sulphur dioxide, black carbon, organic carbon and tropospheric ozone with its precursors are included in the same way as in the IPCC AR5 WGIII assessment. Many air-pollutant species have a common source, and some cool the atmosphere while others warm it. Hence, the cooling or warming effect of reducing these pollutants will depend on the precise mixture that is being reduced. While the Copenhagen Accord pledges do not target these species, integrated assessment models provide trends of air-pollutant emissions consistent with the overall changes in the energy system. In the scenarios analysed in this chapter, air pollutants thus are assumed to change in accordance with changes in carbon dioxide emissions.

Data for determining the probability of scenarios staying within 1.5 °C and 2 °C limits were taken from the IPCC AR5 scenario database. These data were computed with the probabilistic carbon-cycle and climate model MAGICC (Meinshausen *et al*., 2011a; Meinshausen *et al*., 2011b) in a setup that closely simulates the global temperature response to greenhouse gas emissions of the most complex climate models (Rogelj *et al*., 2012). This setup is in line with the most recent Working Group I assessment (Jones *et al*., 2013) and takes into account recent conjectures about a lower climate sensitivity (Rogelj *et al*., 2014). While this approach provides a single consistent framework for the assessment of temperature outcomes, the probabilities reported here depend on this particular framework and do not take into account uncertainty about the model structure. Temperature increase is computed relative to the 1850–1900 period, which is referred to as pre-industrial levels.

For the analyses in this chapter, we focus on scenarios that limit warming to below 2 °C by the end of the 21st century; and scenarios that limit warming below 1.5 °C by the end of the 21st century. Note that scenarios that stay within the 2 °C limit up to 2100, but also have increasing temperatures during that year, might still exceed 2 °C in the next century. This analysis further uses methodologies described in the literature (Rogelj et al., 2011).

warming. Also as noted above, the feasibility of deploying large-scale technologies for global net negative carbon dioxide emissions is uncertain (Fuss *et al*., 2014; Box 2.3). Hence, it is important to investigate if negative emissions can be avoided[15].

Constraints on global carbon dioxide emissions for limiting warming to below 2 °C

The analysis of scenarios has led to the following findings:

[15] It is worth noting that even some scenarios that do not achieve net negative global carbon dioxide emissions do assume that negative emissions technologies (such as bio-energy in combination with carbon-capture and storage (BECCS)) are used to partly offset positive emissions. Furthermore, the land-use and forestry sector (not accounted for in energy and industry-related carbon dioxide emissions) can also contribute to reaching global net negative carbon dioxide emissions, for example, through afforestation. Scenarios are grouped based on their energy and industry-related emissions only, because the main technological uncertainties surrounding negative emissions (related to BECCS) are reflected most in these sectors.

1. Carbon neutrality is reached around 2065 (range: 2055–2070) under the subset of least-cost 2020 scenarios, which – as noted above – may be more consistent with the current pathway of emissions up to 2020 than other scenario subsets. Here carbon neutrality means that carbon dioxide emissions[16] from society are net zero on the global scale. Net zero implies that any remaining carbon dioxide emissions are simultaneously compensated by the same amount of carbon dioxide uptake (negative emissions) so that the net input of carbon dioxide to the atmosphere due to human activities is zero.
2. Almost all scenarios in the IPCC AR5 scenario database with a likely chance of limiting warming to below 2 °C reach carbon neutrality at some point in the second half of this century (Figure 2.4, panels a–d).
3. If emissions up to 2020 would be lower than in the least-cost 2020 scenarios, the carbon dioxide emissions budget would be used up less quickly, and the timing of carbon neutrality could be postponed by about 5–15 years. Hence, increasing ambition over the next few years would postpone by several years the difficult challenge of reaching net zero emissions.
4. In the scenario database from the IPCC, all least-cost 2020 scenarios assume that net negative carbon dioxide emissions are needed at some point during this century to stay within the 2 °C limit. These scenarios further assume that carbon dioxide removal technologies such as bio-energy with carbon capture and storage (BECCS) will be implemented. The uncertainty around these technologies is discussed in Box 2.3. The scenarios also indicate that the higher the emissions in the near term, the

Box 2.3: Negative emissions

Negative carbon dioxide emissions, the active removal of carbon dioxide from the atmosphere, can be achieved by several means. These include afforestation or reforestation, carbon dioxide storage in combination with direct-air-capture, and BECCS (Tavoni and Socolow, 2013). BECCS is a measure that is applied often in model-based studies because of its attractive costs and high potential.

However, the viability of large-scale BECCS deployment depends on overcoming some critical barriers. Fuss *et al*. (2014) identified four:

1: physical and resource constraints (such as water availability), including the sustainability of large-scale deployment relative to other land- and biomass-related needs such as food security and biodiversity conservation, and the presence of safe, long term storage capacity for the captured carbon dioxide;
2: the response of natural land and ocean carbon sinks to negative emissions;
3: the costs and financing of an untested technology; and
4: socio-institutional barriers, such as public acceptance of large-scale carbon capture and storage and large-scale bioenergy production (UNEP, 2012; van Vuuren *et al*., 2013), and the related deployment policies.

Furthermore, the real-world availability of bioenergy is limited by many factors which are not fully represented in models (Creutzig *et al*., 2012) and current estimates from integrated assessment models of total mitigation potential vary greatly, sometimes by a factor of three (Tavoni and Socolow, 2013). Importantly, integrated assessment models also show that stringent climate targets can be achieved without BECCS (Riahi *et al*., 2012), or with just enough BECCS such that carbon dioxide emissions from energy and industry are net zero.

[16] Carbon dioxide emissions refers to the sum of carbon dioxide emissions from energy, industry, and land use/land cover change.

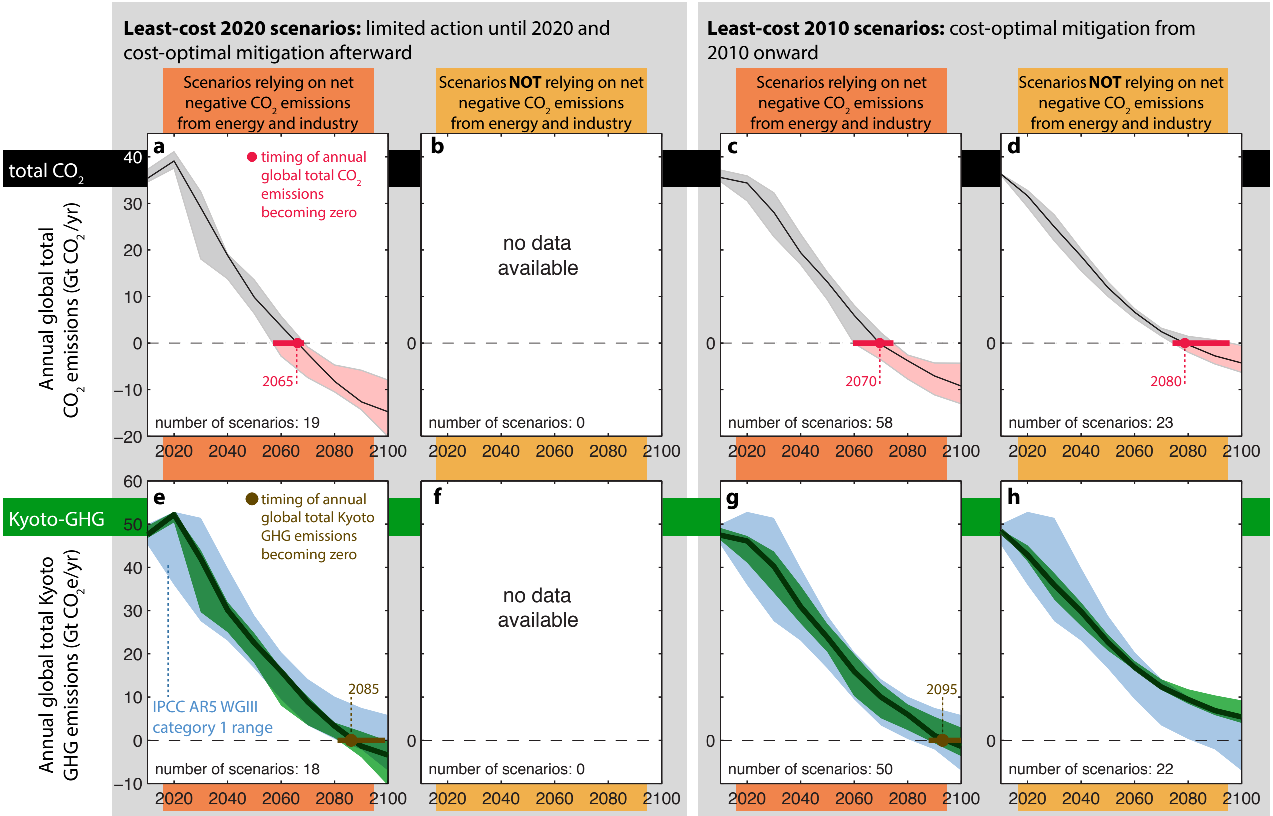

Figure 2.4: Overview of global total carbon dioxide emissions (top row) and global total greenhouse gas emissions – the sum of emissions of all greenhouse gases listed in the Kyoto Protocol

See Footnote 5 for a listing of these gases. The figure shows scenarios that assume limited emissions reductions until 2020 and least-cost emission pathways thereafter (least-cost 2020 scenarios panels a, b, e, and f) and scenarios that assume least-cost emission pathways from 2010 onwards (least-cost 2010 scenarios panels c, d, g, and h). Scenarios with negative levels of global energy and industry-related carbon dioxide emissions are shown in panels a, c, e, and g, and without in panels b, d, f, and h. More details are provided in the text. For each case, the median (solid lines) and the 20th–80th percentile range (shaded areas) are provided. Additionally, for comparison, the range of scenarios included in Category 1 of the IPCC AR5 WGIII assessment is shown in light blue shaded ranges in panels e-h.

larger the negative emissions required later in the century to stay within the carbon dioxide emissions budget (Table 2.1).

5. Scenarios with higher emissions in the near term, least-cost 2020 scenarios, exhaust the carbon dioxide emissions budget more quickly than scenarios with lower emissions in the first few years of the scenario period (least-cost 2010 scenarios). Therefore, scenarios with higher initial emissions must reduce their emissions more rapidly later to stay within the 2 °C limit and/or rely more strongly on negative emission technologies.

Data underlying these findings are provided in Table 2.1. Aiming for only a medium rather than likely chance of staying within the 2 °C limit does not affect the above conclusions (Appendix 2-C).

To sum up, there is a trade-off between postponing near term emissions reductions and having to reduce emissions more rapidly and stringently later. The more that action is delayed in the near term and the greater the reliance on negative emissions later, the earlier the timing of net zero global total carbon dioxide emissions.

Constraints on total greenhouse gas emissions for limiting warming to below 2 °C

The previous section describes the carbon dioxide emission budgets consistent with a 2 °C limit.

Table 2.1: Overview of global cumulative carbon dioxide emissions (CO_2 emission budgets) between 2015 and 2100 consistent with scenarios having a likely chance of limiting global temperature increase to 2 °C during the 21st century

"Likely" chance (>66%)	Global carbon dioxide emissions budgets (Gt CO_2)			
Limited action until 2020 and cost-optimal mitigation afterwards				
Scenarios relying on net negative CO_2 emissions from energy and industry during the 21st century	Number of available scenarios: **19** Year of annual net global CO_2 (including LULUCF) emissions becoming zero*: **2065 (2055-2070)** Average annual reduction rates from 2020 to 2050**: **4.6 (3.4-6.1) per cent per year**			
Time window	*2015–2025*	*2025–2050*	*2050–2075*	*2075–2100*
20th percentile	358	396	-80	-325
median	**370**	**506**	**48**	**-299**
80th percentile***	391	578	98	-148
Scenarios **NOT** relying on net negative CO_2 emissions from energy and industry during the 21st century	Number of available scenarios: **0 (none)** Year of annual net global CO_2 (including LULUCF) emissions becoming zero*: **no data** Average annual reduction rates from 2020 to 2050**: **no data**			
Time window	*2015–2025*	*2025–2050*	*2050–2075*	*2075–2100*
20th percentile	No data	No data	No data	No data
median	**No data**	**No data**	**No data**	**No data**
80th percentile***	No data	No data	No data	No data
Optimal mitigation from 2010 onwards				
Scenarios relying on net negative CO_2 emissions from energy and industry during the 21st century	Number of available scenarios: **58** Year of annual net global CO_2 (including LULUCF) emissions becoming zero*: **2070 (2060-2075)** Average annual reduction rates from 2020 to 2050**: **3.1 (2.5-4.0) per cent per year**			
Time window	*2015–2025*	*2025–2050*	*2050–2075*	*2075–2100*
20th percentile	296	455	-23	-259
median	**340**	**542**	**110**	**-156**
80th percentile***	351	607	157	-85
Scenarios **NOT** relying on net negative CO_2 emissions from energy and industry during the 21st century	Number of available scenarios: **23** Year of annual net global CO_2 (including LULUCF) emissions becoming zero*: **2080 (2075-2095)** Average annual reduction rates from 2020 to 2050**: **3.3 (3.0-3.6) per cent per year**			
Time window	*2015–2025*	*2025–2050*	*2050–2075*	*2075–2100*
20th percentile	290	427	111	-95
median	**312**	**506**	**142**	**-51**
80th percentile***	324	533	159	19

* Rounded to nearest 5 years. Format: median (20th percentile – 80th percentile).
** Reduction rates are computed as compound annual growth rates.
*** As higher emissions in the near term have to be compensated by deeper reductions later, emitting 80th percentile budgets over the entire century would not result in a *likely* chance of limiting warming to below 2°C.

Notes: Data refers to global total (energy, industry and LULUCF) carbon dioxide emissions. For results consistent with a "medium" (50–66 per cent) chance, see Appendix 2-C. A comparison of these results with IPCC AR5 WGIII data is provided in Appendix 2-D.

Table 2.2: Overview of global emissions of total greenhouse gases in 2020, 2025, 2030, 2050 and 2100 consistent with scenarios with a likely (greater than 66 per cent) chance of limiting global temperature increase to below 2 °C during the 21st century, respectively

"Likely" chance (>66%)	Annual emission of global total greehouse gases (Gt CO_2e/yr)				
Limited action until 2020 and cost-optimal mitigation afterwards					
Scenarios relying on net negative CO_2 emissions from energy and industry during the 21st century	Number of available scenarios: **18** Year of annual net global Kyoto-greenhouse gas emissions becoming zero†: **2085 (2080-2100)** Average annual reduction rates from 2020 to 2050‡: **2.8 (2.4-3.6) per cent per year**				
Year	*2020*	*2025*	*2030*	*2050*	*2100*
median*	**52**	**47**	**42**	**22**	**-3**
range and spread**	49(50/53)55	39(40/48)50	29(30/44)44	17(18/25)29	-11(-10/0)0
Scenarios **NOT** relying on net negative CO_2 emissions from energy and industry during the 21st century	Number of available scenarios: **0 (none)** Year of annual net global Kyoto-greenhouse gas emissions becoming zero†: **no data** Average annual reduction rates from 2020 to 2050‡: **no data**				
Year	*2020*	*2025*	*2030*	*2050*	*2100*
median*	**no data**	**no data**	**no data**	**no data**	**no data**
range and spread**	no data	no data	no data	no data	no data
Optimal mitigation from 2010 onwards					
Scenarios relying on net negative CO_2 emissions from energy and industry during the 21st century	Number of available scenarios: **50** Year of annual net global Kyoto-greenhouse gas emissions becoming zero†: **2095 (2090-after 2100)** Average annual reduction rates from 2020 to 2050‡: **2.1 (1.4-2.6) per cent per year**				
Year	*2020*	*2025*	*2030*	*2050*	*2100*
median*	**46**	**43**	**40**	**24**	**-1**
range and spread**	22(41/47)49	23(38/45)47	23(34/44)46	14(20/27)33	-10(-4/3)7
Scenarios **NOT** relying on net negative CO_2 emissions from energy and industry during the 21st century	Number of available scenarios: **22** Year of annual net global Kyoto-GHG emissions becoming zero†: **after 2100 (after 2100-after 2100)** Average annual reduction rates from 2020 to 2050‡: **2.1 (1.9-2.4) per cent per year**				
Year	*2020*	*2025*	*2030*	*2050*	*2100*
median*	**43**	**39**	**36**	**23**	**5**
range and spread**	36(41/45)48	27(37/42)44	18(32/38)41	13(20/24)25	3(4/9)13

* Rounded to the nearest 1 Gt CO_2e/yr.
** Rounded to the nearest 1 Gt CO_2e/yr. Format: minimum value (20th percentile/80th percentile) maximum value.
† Rounded to nearest 5 years. Format: median (20th percentile – 80th percentile).
‡ Reduction rates are computed as compound annual growth rates.

Notes: Data refer to the sum of emissions of all greenhouse gases listed in the Kyoto Protocol (see footnote 5 for a listing of these gases). For results consistent with a "medium" (50–66 per cent) chance, see Appendix 2-C. A comparison of these results with IPCC AR5 WGIII data is provided in Appendix 2-D.

However, society produces not only carbon dioxide emissions but also substantial amounts of non-carbon dioxide greenhouse gas emissions such as methane, nitrous oxide and hydrofluorocarbons, and these also make an important contribution to global warming. Indeed, many of the scenarios from the IPCC scenario database take account of both carbon dioxide and the non-carbon dioxide gases listed in the Kyoto Protocol[17]. Hence, to get a more comprehensive picture of the emission

[17] See footnote 5 for a listing of these gases.

pathways consistent with climate targets we consider what total[18] greenhouse gas emission pathways – carbon dioxide plus non-carbon dioxide – stay below the 2 °C limit. The following conclusions can be drawn from the analysis of total greenhouse gas emissions scenarios that have a likely chance of staying within the 2 °C limit:

1. More than half of the scenarios in the IPCC AR5 scenario database that limit warming to below 2 °C with a likely chance reach net zero global total greenhouse gas emissions in the second half of this century.
2. All scenarios in the subset of least-cost 2020 scenarios, which, as noted above, may be more consistent with the current pathway of emissions up to 2020, reach net zero total greenhouse gas emissions some time between 2080 and 2100, or have nearly net zero total greenhouse gas emissions in 2100[19].
3. The timing of net zero global total emissions does not change much for the least cost 2010 scenarios. In that case the timing of net zero emissions would only be pushed back by about 10 years.
4. Least-cost 2010 scenarios show a median emissions level of 44 Gt CO_2e per year in 2020 (range: 41–47).
5. Least-cost 2020 scenarios show a median emissions level of 52 Gt CO_2e per year in 2020 (range: 50–53). While this figure is much higher than in scenarios that begin stringent emission reductions in 2010 – least-cost 2010 scenarios – it is still exceeded by the expected level of emissions under almost all the pledge cases (Chapter 3).
6. Looking further into the future, global emissions decline in all scenario groupings considered. In the least-cost 2020 scenarios, median global emissions of total greenhouse gases for 2025, 2030 and 2050 are 47, 42, and 22 Gt CO_2e per year respectively (Table 2.2).

Constraints for limiting warming to below 1.5 °C

Working Group III of the IPCC AR5 indicated that only a small number of studies have identified feasible total greenhouse gas emission pathways that are consistent with staying below a 1.5 °C limit up to 2100 with at least a 50 per cent chance. This small group of studies agree that staying within 1.5 °C requires:

1: immediate and strong mitigation action;
2: the rapid upscaling of the full portfolio of mitigation technologies; and
3: development along a low-energy demand trajectory (IPCC, 2014).

Within these studies, only a small number of scenarios meet the 1.5 °C target with at least a 50 per cent chance, and have least-cost pathways beginning in 2010. Emission levels in one set of these scenarios are 37–41 Gt CO_2e in 2020, 27–31 Gt CO_2e in 2030, and 13–17 Gt CO_2e in 2050 (Rogelj *et al.*, 2013b). Emissions levels in another set are 39–43 Gt CO_2e in 2020, 27–35 in 2030, and 6–10 Gt CO_2e in 2050 (Luderer *et al.*, 2013b).

An even smaller number of scenarios meet the 1.5 °C target with at least a 50 per cent chance and have least-cost emissions pathways beginning in 2020 – and therefore, have higher emissions up to 2020.

2.3.4 Implications of later action

As noted above, recent trends in global emissions imply that the world is not following a least-cost pathway of early mitigation action for limiting global temperature increase to either 1.5 °C or 2 °C (Friedlingstein *et al.*, 2014). An obvious advantage of delaying mitigation action is that costs are not incurred today. On the other hand, many recent studies[20], including the IPCC AR5, have shown that delaying mitigation actions will intensify

[18] Total greenhouse gas emissions is used here to mean the global emissions of the Kyoto gases as listed in Footnote 5.

[19] Four scenarios in this subset show total greenhouse gas emissions in 2100 which are below 0.25 Gt CO_2e per year, but still above zero.

[20] For example, van Vliet *et al*. (2012); Rogelj *et al.* (2013a,b); Riahi *et al.* (2013); Luderer *et al.*, (2013a,b); Kriegler *et al.* (2014a) and the IPCC AR5 WGIII report (Clarke *et al.*, 2014).

the challenges to limit global warming to 1.5 °C or 2 °C[21]. In general, IPCC AR5 found (with high confidence) that postponing further mitigation efforts to 2030 beyond current country pledges would substantially hinder the transition to lower long-term emissions levels and highlights that this postponement would narrow the range of options for staying within the 2 °C limit with a likely chance. The IPCC highlighted that many models were unable to produce scenarios that keep warming to below 2 °C with about 50 per cent chance, when starting from emissions in 2030 that are greater than 55 Gt CO_2e.

Higher near term emission levels require very fast medium term emission reductions

Delaying mitigation action and allowing higher emission levels in the near term means that faster emission reductions are required later to stay within the same carbon dioxide emissions budget. For example, scenarios that delay stringent action until 2020 (least-cost 2020 scenarios) reduce their carbon dioxide emissions by around 4.6 per cent per year[22] after 2020 as compared to scenarios with earlier action (least-cost 2010 scenarios) which fall by 3.1–3.3 per cent per year during the same period (Table 2.1). Furthermore, the IPCC showed that scenarios with stringent mitigation delayed until 2030 required twice as rapid a reduction in carbon dioxide emissions after 2030 as compared to those that had begun stringent reductions in 2010 – for the case of staying within the 2 °C limit (IPCC, 2014). In addition, the AMPERE study found that scenarios with modest emission reductions until 2030 used up about 70 per cent of the carbon dioxide emissions budget consistent with the 2 °C limit by that date (Bertram *et al.*, 2013; Riahi *et al.*, 2013). Furthermore, it was noted that immediate and stringent emission reductions are essential in scenarios that stay below the 1.5 °C limit by 2100 (Luderer *et al.*, 2013b; Rogelj *et al.*, 2013a; IPCC, 2014).

Delay in mitigation causes lock-in of carbon intensive infrastructure

Scenarios with limited near term action have fewer options for reducing emissions if concerted action is delayed until after 2020 or 2030. This is because of carbon lock-in – the continued construction of high-emissions fossil-fuel infrastructure unconstrained by climate policies (Bertram *et al.*, 2013; Luderer et al., 2013a; Rogelj et al., 2013a; Johnson *et al.*, 2014). Unless comprehensive and ambitious climate policies are put into place, the world will continue to expand its carbon- and energy-intensive infrastructure, and will not sufficiently incentivize the development and scale-up of climate-friendly technologies. As an example, the capacity of coal-fired power plants grows by 50 per cent by 2030, relative to current levels, under some later action scenarios in the AMPERE study (Bertram *et al.*, 2013).

Other studies have shown that a large fraction of carbon-intensive infrastructure, particularly coal power plants, will need to be shut down prematurely if the 2 °C target is to be achieved (Johnson *et al.*, 2014) – an example of stranded assets. Delaying stringent reductions until 2030 will result in such stranded assets in the order of hundreds of billions of dollars (Bertram *et al.*, 2013; Johnson *et al.*, 2014). For example, a recent study (Johnson *et al.*, 2014) estimates that, over the period 2011–2050, global investments associated with stranded coal-fired power plant capacity could more than triple (from US$ 165 to US$ 550 billion) if stringent mitigation is not achieved by 2030 (and the 2 °C target is met through later, drastic mitigation efforts). This happens because weak restrictions on emissions over the next few years are assumed to encourage/allow the expansion of conventional coal-fired power plants. As a result, a larger number of coal-fired power plants might be faced with stringent emission restrictions later and be forced to close before the end of their usual life.

[21] These paragraphs update the discussion of this topic in UNEP (2013) .

[22] Emission reduction rates are typically computed as compound annual growth rates. However, such an approach cannot deal with emissions becoming negative at some point during the assessed time period.

The same lock-in effect applies to lost opportunities for energy efficiency (Chapter 4). *The Global Energy Assessment* (GEA[23]; Riahi *et al.*, 2012) shows the critical importance of energy efficiency measures for limiting warming to below 2 °C, and similar findings are valid for returning warming to below 1.5 °C (Luderer *et al.*, 2013b; Rogelj *et al.*, 2013a; Rogelj *et al.*, 2013b). Later-action scenarios tend to further lock-in power plants, buildings and other infrastructure with low levels of energy efficiency. This makes the transition to a high-energy-efficiency future more difficult, and puts a greater burden on alternative emission reduction measures.

Delay in mitigation can slow the transformation of the energy system

Recent research has shown that the share of zero- and low-carbon energy sources[24] in the world's energy economy has to substantially increase in order to stay within atmospheric levels of greenhouse gases consistent with the 2 °C limit. One estimate is that a 3–4-fold increase is needed between 2010 and 2050 (Riahi *et al.*, 2013; IPCC, 2014). The question is how fast this growth has to take place. On one hand, least-cost scenarios, beginning in 2010, achieve this share through a smooth transition and roughly a doubling of the low-carbon energy share every 20 years. On the other hand, scenarios delaying action until later need to achieve this objective at a much faster pace. For example, scenarios with delays up to 2030, need to scale up the low-carbon share of the energy economy at twice the pace of least-cost scenarios beginning in 2010 (Riahi *et al.*, 2013; IPCC, 2014). Moreover, the lack of near term climate policies is also assumed to hinder the scaling up of low-emission, green-energy technologies (Eom *et al.*, 2013), and hinder technological learning and development as well.

Early policy signals are needed to plan for later action

Even if near term mitigation actions are delayed, it is important to begin sending strong and reliable policy signals to industry, municipalities and other sectors of society that stringent emissions reductions will be necessary over the medium term – for example, laws or regulations that call for specific emission reductions or ceilings at some future date. Without clear signals, industry will lock-in carbon- and energy-intensive infrastructure as explained above.

Delay in mitigation leads to higher overall costs and economic challenges

Scenarios with later action have lower mitigation costs in the near term and this implies a lower burden on current economic growth but larger overall mitigation costs. These scenarios also have larger economic challenges during the transition towards a comprehensive climate policy regime, including substantial impacts on global economic growth and energy prices (Clarke *et al.*, 2009; Jakob *et al.*, 2012; OECD, 2012; Kriegler *et al.*, 2014a; Luderer *et al.*, 2013a; Luderer *et al.*, 2013b; Riahi *et al.*, 2013; Rogelj *et al.*, 2013a; Rogelj *et al.*, 2013b; Clarke *et al.*, 2014). The longer the delay, the higher costs become. The IPCC indicates that delaying stringent reductions to 2030 would increase mitigation costs during the period 2030–2050 by around 40 per cent compared to scenarios without delays (Clarke *et al.*, 2014). The cost penalty of later action depends on:

1: when comprehensive mitigation actions finally begin;
2: the magnitude of emission reductions up to that point; and
3: the future availability of technologies.

Furthermore, delaying emission reductions in the near term shifts the burden of mitigation costs

[23] The full report is available at: http://www.globalenergyassessment.org/

[24] Renewables, nuclear energy, fossil fuel energy with carbon capture and storage, or biofuels with carbon capture and storage.

to later generations (OECD, 2012; Luderer *et al.*, 2013b; Rogelj *et al.*, 2013a; Clarke *et al.*, 2014).

Finally, later-action scenarios also have higher economic costs, exclusive of mitigation costs, during the transition from modest early action to later more comprehensive action (Kriegler *et al.*, 2014a; Luderer *et al.*, 2013a; Luderer *et al.*, 2013b). These transitional costs increase strongly with further delay.

Delay in mitigation reduces societal choices

The more emission reductions are delayed, the greater society's dependence on future unproven technologies[25], reducing its options and choices for the future (Luderer *et al.*, 2013b; Riahi *et al.*, 2013; Rogelj *et al.*, 2013a). Many later-action scenarios assume that the full portfolio of mitigation options represented in the models is available, including unproven negative emissions technologies such as BECCS (Box 2.3). However, costs will increase if it turns out that anticipated technologies are not available, because of technology failure or because society chooses not to deploy them (Kriegler *et al.*, 2014b; Luderer *et al.*, 2013b; Rogelj *et al.*, 2013b; Clarke *et al.*, 2014).

Delay in mitigation leads to higher climate risks

Scenarios with later action increase the risks of climate impacts in the following ways:

First, the risk of temporarily exceeding climate limits is higher because of higher initial emission levels (Clarke *et al.*, 2009; den Elzen *et al.*, 2010; van Vliet *et al.*, 2012; Kriegler *et al.*, 2013; Luderer *et al.*, 2013a; Rogelj *et al.*, 2013a; Schaeffer *et al.*, 2013). Overshooting temperature limits, or prolonging the overshoot period, implies a greater risk of large-scale and possibly irreversible changes in the climate system – see Lenton *et al.* (2008) for examples of such changes. The extent to which such overshooting increases the risk of these impacts is very uncertain.

Second, the pace of temperature increase in the near to medium term is higher (den Elzen *et al.*, 2010; van Vliet *et al.*, 2012; Schaeffer *et al.*, 2013) and this can imply more rapid climate impacts and require quicker adaptation. For example, based on results from 11 integrated assessment models, Schaeffer *et al.* (2013) found that later-action scenarios meeting the 2 °C limit have, on average, a 50 per cent higher rate of decadal temperature increase in the 2040s compared with least-cost scenarios beginning in 2010 – 0.3 °C instead of 0.2 °C per decade.

Third, postponing stringent mitigation increases the risk of exhausting carbon dioxide emission budgets. The risk comes from the fact that the steep reductions required to compensate for higher near-term emissions may not materialise. This may happen because of unanticipated technology failures (Riahi *et al.*, 2013; Clarke *et al.*, 2014) or the unwillingness of future policymakers to take on the required high costs of mitigation.

Fourth, when action is delayed, various options to achieve stringent levels of climate protection are increasingly lost (Luderer *et al.*, 2013b; Rogelj *et al.*, 2013a; Rogelj *et al.*, 2013b). One sign of this is that a declining number of models are able to identify feasible emission pathways that stay within a 1.5 °C or 2 °C limit with increasing delays (IPCC, 2014).

Delay in mitigation forgoes co-benefits

The IPCC AR5 WGIII report (IPCC, 2014) identified a large number of co-benefits of greenhouse gas mitigation, such as reduced costs for achieving air quality and energy security objectives, improved human health, reduced crop yield losses, and lower adverse impacts on ecosystems. Delaying mitigation action also implies that these co-benefits will be forgone while emissions remain high.

[25] As an example of technological dependency, it was found that only two out of nine models in the AMPERE study could reach a long-term 450 parts per million (ppm) carbon dioxide concentration target (and therefore could comply with the 2 °C target) without scaling up carbon capture and storage (Riahi *et al.*, 2013). A similar dependency is found for other mitigation technologies (*ibid*, Rogelj *et al.*, 2013b).