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Mitigation in the Context of the Paris Agreement

A synthesis of the scientific literature related to 1.5°C

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Summary - sammendrag

This synthesis provides an overview of the recent scientific literature related to the Paris Agreement global mitigation goals. Key characteristics of scenarios in line with limiting warming to below 1.5°C in 2100 with 50% probability have been identified in the post-AR5 literature: (1) no scenarios are available which peak global greenhouse gas emissions later than 2020 and comprehensive emission reductions thus need to occur over the 2015-2025 time period; (2) global net zero CO2 emissions are achieved around mid-century, 10 to 20 years earlier than in scenarios that limit warming to below 2°C with a 66% probability, and CO2 reductions beyond global net zero are achieved afterwards to peak and decline global temperatures. This requires CO2 to be removed actively from the atmosphere; (3) additional emission reductions coming mainly from CO2 compared to 2°C scenarios with 66% probability, while also non-CO2 greenhouse gas need to be reduced but not beyond what is already assumed for 2°C. Furthermore, (4) energy supply is rapidly and profoundly decarbonized over the next two decades, and (5) energy efficiency is key resulting in lower demand in hard-to-decarbonize sectors, like industry, buildings, and transportation.

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Andersen, Terje H.T.

Content

Summary

The 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) marks an important milestone in the international response to the threat of climate change. It includes a wide set of goals covering the areas of mitigation, adaptation, and finance, amongst others. Here we zoom in on one of these aspects and provide an overview of the recent scientific literature related to the Paris Agreement global mitigation goals.

The Paris Agreement's goal to limit global mean temperature increase to well below 2°C and to pursue efforts to limit it further to 1.5°C comes with clear geophysical consequences. Limiting warming to below any global temperature limit implies a cap on the total amount of CO_2 (carbon dioxide) we can ever emit into the atmosphere, or in other words, a global carbon budget. New research that appeared after the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) now shows that temporarily overspending the global carbon budget and later returning to within the budget by means of carbon dioxide removal from the atmosphere is a risky strategy. Non-linear feedbacks in the climate system related to the melting of permafrost increase the amount of CO_2 that has to be removed after a budget overshoot. A further implication of global CO_2 budgets is that net global CO_2 emissions have to become zero at some point in the future, irrespective of the global maximum temperature goal.

Recent studies show how and by when this is achieved in scenarios that limit warming to well below 2°C and 1.5°C relative to preindustrial levels. Key characteristics of scenarios in line with limiting warming to below 1.5°C in 2100 with 50% probability have been identified in the post-AR5 literature: (1) no scenarios are available which peak global greenhouse gas emissions later than 2020 and comprehensive emission reductions thus need to occur over the 2015-2025 time period; (2) global net zero CO_2 emissions are achieved around mid-century, 10 to 20 years earlier than in scenarios that limit warming to below 2°C with a 66% probability, and CO_2 reductions beyond global net zero are achieved afterwards to peak and decline global temperatures. This requires CO_2 to be removed actively from the atmosphere; (3) additional emission reductions coming mainly from CO_2 compared to 2°C scenarios with 66% probability, while also non-CO_2 greenhouse gas need to be reduced but not beyond what is already assumed for 2°C. Furthermore, (4) energy supply is rapidly and profoundly decarbonized over the next two decades, and (5) energy efficiency is key resulting in lower demand in hard-to-decarbonize sectors, like industry, buildings, and transportation.

The Paris Agreement also sets a global goal of reaching a balance between anthropogenic emissions and removals of greenhouse gases in the second half of the century. The carbon budget concept assessed by the IPCC implies that, unless this balance is applied to anthropogenic emissions and anthropogenic removals, global temperature will continue to rise for multiple decades to centuries instead of peak and stabilize.

1. Introduction

The 2015 Paris Agreement (UNFCCC, 2015b) of the United Nations Framework Convention on Climate Change (UNFCCC) marks an important milestone in the international response to the threat of climate change. Since the establishment of the UNFCCC countries have worked towards achieving the UNFCCC's ultimate objective of preventing *"dangerous anthropogenic interference with the climate system"* (UNFCCC, 1992). In 2015, the international climate policy community took the next step by translating the UNFCCC's ultimate objective into a quantified temperature limit. This is expressed in Article 2 of the Paris Agreement, which defines the aim of the Paris Agreement as *"holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, […]"*.

Besides a long-term temperature goal, the Paris Agreement also provides a long-term mitigation goal, which states that *"Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, […], and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century […]"* (UNFCCC, 2015b). Science has thus been given a critical role in the framework established by the Paris Agreement.

Such a strong involvement of science is not new for the UNFCCC process. Since the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988, scientific assessments have informed international policy and assisted in developing scientifically robust greenhouse gas inventories. Also during the process leading up to the Paris Agreement science played an important role, and an elaborated science-policy dialogue process, known as the 'Structured Expert Dialogue' (SED), was established. This process identified important research gaps in relation to the science of both the impacts of and the pathways towards a temperature limit of 1.5°C (UNFCCC, 2015a), which led the UNFCCC to invite both the research community and the IPCC to address these gaps in understanding.

The IPCC has meanwhile accepted this invitation and has started the preparations for a Special Report on *"the impacts of global warming of 1.5°C above preindustrial levels and related global greenhouse gas emission pathways"* (IPCC, 2016), to be finalized by 2018. The scoping meeting for this report took place from 15 to 18 August 2016 in Geneva, Switzerland, and the corresponding approval session for the report outline is scheduled at the 44th IPCC plenary which takes place from 17-20 October 2016 in Bangkok, Thailand.

This briefing aims at providing a synthesis of the peer-reviewed literature on global mitigation pathways in the context of the Paris Agreement, and particularly related to a global temperature limit of 1.5°C relative to preindustrial. The briefing starts out with a discussion of the importance and implications of various interpretations of the Paris Agreement long-term temperature goal. The remainder then covers three main aspects: (1) The geophysical implications of a 1.5°C global temperature goal, in particular the implications for the global carbon budget; (2) A discussion of the main differences between mitigation pathways leading to limiting warming to 1.5°C or 2°C relative to preindustrial levels; and (3) issues related to the balancing of sources and sinks for achieving climate stabilisation.

2. Paris Agreement Temperature Goal Interpretation

The Paris Agreement's long-term temperature goal is *"holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels"*. This wording is much more precise than the UNFCCC's ultimate objective of preventing dangerous anthropogenic interference with the climate system, but still allows for some interpretation. For example, the precise meaning of 'well below 2°C' remains undefined. This wording can be translated in more operational terms by defining a limit for maximum warming which corresponds to a specific level 'well below 2°C', like 1.8°C, 1.7°C, 1.6°C, or 1.5°C. Such a translation should also include the probability by which one attempts to achieve this goal, for example a 50%, 66%, 75% or greater probability. Furthermore, the Paris Agreement states that peak warming should be kept to well below 2°C together with the requirement to pursue efforts to limit the temperature increase to 1.5°C. Varying interpretations are possible as to whether these 1.5°C efforts have to aim at limiting peak warming to 1.5°C or warming after temporarily exceeding that limit. Assuming that global temperature increase can exceed a particular temperature limit for a certain time before being brought back below it is often referred to as a temperature overshoot. In such a case, issues about how long and how high the temperature limit is allowed to be exceeded require further clarification, in light of the anticipated additional climate impact and mitigation risks, like the reliance of temperature overshooting on carbon dioxide removal. Finally, targets referring to different temperature levels can still be internally consistent (see Figure 1). For example, scenarios limiting warming to below 2°C during the 21st century with at least 80% probability also provide a 50% probability of limiting warming to 1.5°C by 2100, after a temporary overshoot.

These various possible interpretations are not a scientific issue to solve, but can only be resolved through clarifications and discussion between Parties within the UNFCCC. However, it is important to highlight them upfront in scientific assessments. The studies underlying the quantitative scientific synthesis presented in this briefing all assess implications of particular interpretations of long-term climate targets. Importantly, the inclusion of a particular interpretation of the Paris Agreement's long-term temperature goal in this briefing does not imply any endorsement, but rather reflects what studies have assumed in order to be able to carry out their analysis.

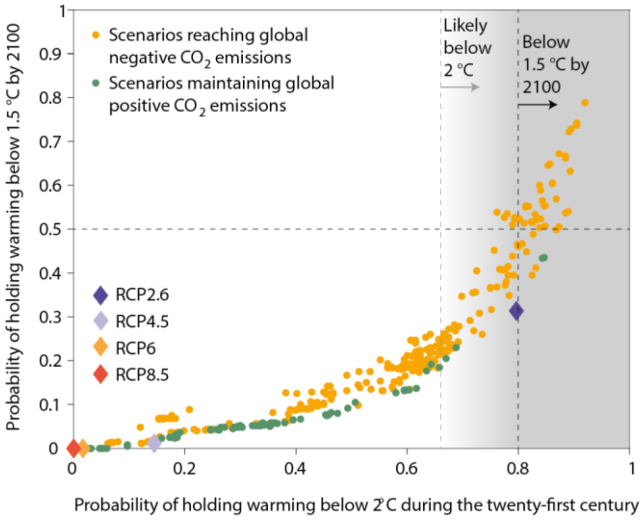

*Figure 1 **Illustration of the consistency of targets that refer to different temperature levels but with varying probabilities of remaining below the respective temperature thresholds. Figure source: Schleussner et al. (2016).***

3. Geophysical Implications

The IPCC Fifth Assessment Report (AR5) firmly established that *"cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond"* (IPCC, 2013). Moreover, this relationship between cumulative CO_2 emissions and temperatures is near-linear. This thus facilitates the definition of so-called CO_2 or carbon budgets: the total amount of CO_2 which should not be exceeded in order to hold global mean temperature increase to below a particular temperature threshold.

3.1 Conceptual Introduction

A conceptual introduction to CO_2 budgets is given in Figure 2. A certain amount of CO_2 emissions (panel A), will lead to increasing atmospheric CO_2 concentrations (panel B), which start declining if CO_2 emissions are put to zero. However, due to the interplay between diminishing CO_2 concentrations and the implied warming due to the already heightened CO_2 concentrations[1] (Held *et al.*, 2010), global mean temperature increase (panel C) remains virtually constant after a total cessation of CO_2 emissions. This allows the definition of a near-linear relationship between cumulative emissions of CO_2 and global mean temperature increase (panel D). This relationship is also referred to as the 'transient climate response to cumulative emissions' (TCRE) and allows the quantification of CO_2 budgets in line with a specific temperature limit. However, CO_2 is not the only human contribution to global mean temperature rise. Non-CO_2 contributions have been significant in the past (Myhre *et al.*, 2013) and are projected to continue to contribute in the future (Figure TFE.8, Figure 1 in the IPCC AR5 Working Group I

[1] This warming is sometimes referred to as 'recalcitrant warming'. If CO_2 concentrations would be kept constant, global temperature would continue to rise, and slowly evolve from its transient or quasi-instantaneous level to its higher, equilibrium level.

Technical Summary (Stocker *et al.*, 2013)). Any net non-CO_2 contribution to global mean temperature rise at peak warming would result in a decrease of the carbon budget (panel E). Furthermore, because of uncertainties in the exact response of the carbon cycle and the climate system, the TCRE relationship is also uncertain. Therefore, pursuing a goal of holding warming to below a particular temperature limit needs to be accompanied by a probability by which this goal is to be achieved. Aiming for higher likelihoods of holding warming to below a temperature limit results in smaller CO_2 budgets (panel F). Finally, aiming for a lower temperature limit with the same likelihood also implies a lower CO_2 budget (panel G).

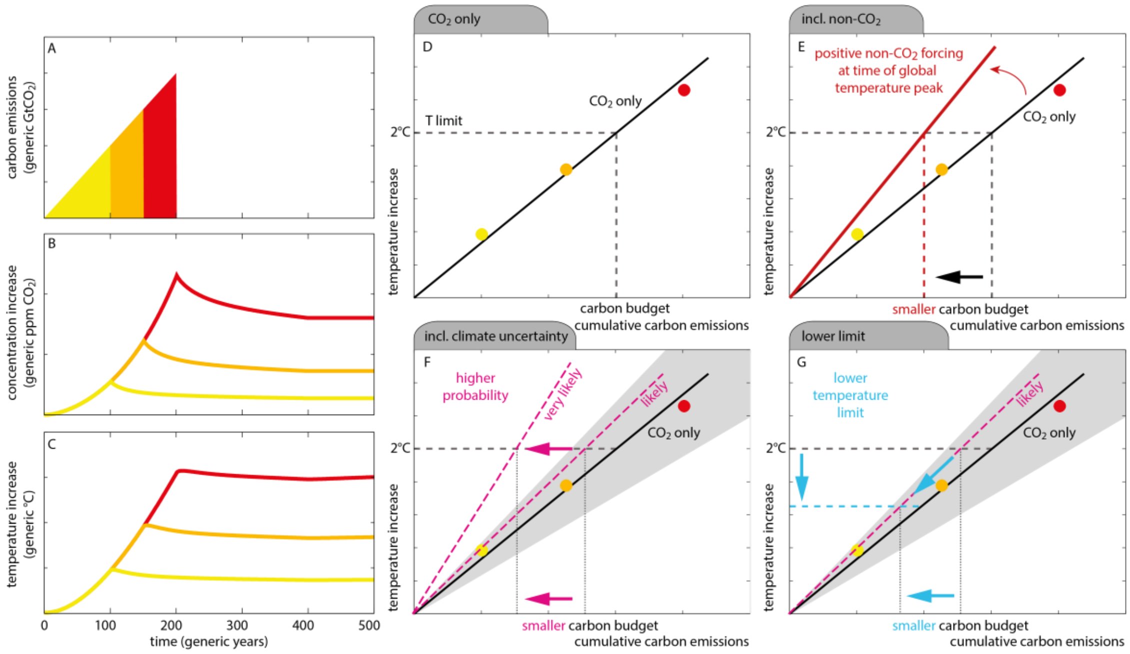

Figure 2 Conceptual illustration of the near-linear relationship between cumulative carbon emissions and global mean temperature increase, and implications for carbon budgets. Illustrations based on a figure from (Knutti and Rogelj, 2015).

3.2 Post-AR5 Insights and Limitations

The IPCC AR5 assessed TCRE to fall *likely* (that is, with greater than 66% probability) between 0.8°C to 2.5°C per 1000 PgC (or about 3670 $GtCO_2$)[2] for cumulative emissions less than about 2000 PgC (or about 7320 $GtCO_2$) until the time at which temperature peak (Collins *et al.*, 2013). This is consistent with the range found in Earth system models in the literature (Gillett *et al.*, 2013). From the assessed IPCC range, budgets were calculated (Stocker *et al.*, 2013) for keeping peak CO_2-induced warming to below 2°C with at least 50% and 66% probability (4440 $GtCO_2$ and 3670 $GtCO_2$ since 1870, respectively). However, these budgets are estimates for the hypothetical case that CO_2 is the only climate forcer. When estimating the budget accounting for the potential contribution of non-CO_2 forcers as in RCP2.6, IPCC AR5 provided a preliminary estimate of 3010 $GtCO_2$ and 2900 $GtCO_2$, respectively. At the same time, IPCC AR5 estimated (IPCC, 2013) that approximately 1890 $GtCO_2$ of carbon was already emitted since 1870 until 2011.

[2] 1 PgC = 10^{15} gC = 10^{9} tC = 1 GtC = 3.6 $GtCO_2$

Post-AR5 research further clarified this picture. Experiments with four Earth System Models have shown that the near-linear relationship between cumulative CO_2 emissions and global mean temperature rise holds even for cumulative emissions up to 18350 $GtCO_2$ (Tokarska *et al.*, 2016)[3], instead of the 7320 $GtCO_2$ cut-off indicated at the time of the AR5. 18350 $GtCO_2$ would be consistent with the lower end of estimated fossil fuel resources (Tokarska *et al.*, 2016; IEA, 2013). Earlier, models of intermediate complexity had shown that the TCRE would decline for cumulative CO_2 emissions higher than 7320 $GtCO_2$ (Herrington and Zickfeld, 2014). These newest findings thus imply that projected warming under the unabated use of available fossil fuel resources would results in more profound climate impacts than previously thought (Tokarska *et al.*, 2016).

IPCC AR5 defines TCRE until peak warming, but new research has now shed light on how the climate system responds under other conditions. A study with an Earth System Model including a detailed coupled ocean has shown that over multi-millennial timescales temperature might further increase and suggests a 20% lower overall CO_2 budget for 2°C when this multi-millennial is also taken into account (Frölicher *et al.*, 2014; Frölicher and Paynter, 2015). Furthermore, TCRE appears to be different for CO_2 from fossil-fuel burning than CO_2 from land-use change (Simmons and Matthews, 2016), not because the CO_2 effect in the atmosphere would be different, but because land-use change CO_2 is accompanied by land cover change which modifies the Earth's reflectivity or albedo.

An important further question regarding CO_2 budgets, in particular related to their use for scenarios which apply negative emissions technologies, is the question of reversibility. Can warming be reversed if we first exceed a specific CO_2 budget, and later try to counteract this CO_2 budget overshoot by actively removing CO_2 from the atmosphere? Studies have shown that global mean temperature rise can be reversible (MacDougall, 2013) and the relative path independence of decadal to century global mean temperature increase for a given CO_2 budget (Herrington and Zickfeld, 2014; Tokarska and Zickfeld, 2015). However, none of these studies took into account the potential release of CO_2 by melting permafrost. Some studies do include such feedbacks (Schneider von Deimling *et al.*, 2015; MacDougall *et al.*, 2015). One found that under a 2°C scenario permafrost melting could release about 70-210 $GtCO_2$ by 2100 and 145-350 $GtCO_2$ by 2300 (Schneider von Deimling *et al.*, 2015). These amounts should be subtracted from earlier estimates of 2°C-consistent budgets. A second study found that the inclusion of permafrost feedbacks would reduce 2°C-consistent budgets from preindustrial by about 10% (MacDougall *et al.*, 2015). The latter study also showed that when taking into account these permafrost feedbacks the reversibility temperature response to cumulative CO_2 emissions breaks down. Overshooting a temperature limit results in smaller long-term CO_2 budgets. Furthermore, besides permafrost carbon stocks (MacDougall *et al.*, 2015; Schneider von Deimling *et al.*, 2015), several other important limitations of the reversibility of changes in key climate system components have been identified, for example, for multi-century sea-level rise (Tokarska and Zickfeld, 2015), or ocean acidification and the marine environment (Mathesius *et al.*, 2015).

This new literature thus shows that exceeding a CO_2 budget and afterwards actively removing CO_2 from the atmosphere so as to return to within the previously defined budget limit, comes with a double penalty. First, the temperature limit is exceeded resulting in more severe

[3] 5000 PgC in the original publication.

climate impacts and with an increasing risk for irreversible impacts, even if temperatures decline again afterwards. Second, to reverse temperature rise, a lower long-term budget has to be assumed and more CO_2 will have to be removed from the atmosphere than the amount initially exceeding the budget. The precise amount by which the compatible CO_2 budget is reduced due to overspending the budget depends on the level and duration of the assumed temperature overshoot. Research has also shown that aiming to achieve multiple climate targets simultaneously (like limiting temperature rise and ocean acidification) would result in a smaller overall CO_2 budget than would be suggested by each of the targets individually (Steinacher *et al.*, 2013).

3.3 Carbon Budget Quantifications for Mitigation Scenarios

Other post-AR5 efforts have focussed on understanding the relationship and differences between the various CO_2 budget estimates available in the literature (Rogelj *et al.*, 2016), and providing updated estimates of CO_2 budgets for achieving specific mitigation targets (Friedlingstein *et al.*, 2014; Rogelj *et al.*, 2015b; Rogelj *et al.*, 2015c; van Vuuren *et al.*, 2016). A review paper on the topic of CO_2 budgets (Rogelj *et al.*, 2016) identified and grouped budgets available in the literature in three categories: budgets for CO_2-induced warming only, budgets for total warming derived from scenarios which exceed the temperature limit of interest (called threshold exceedance budgets), and budgets for total warming derived from scenarios which keep warming to below the temperature limit of interest (called threshold avoidance budgets). Based on scenarios from the IPCC, it was reported that estimates of threshold exceedance budgets consistently overestimate the available CO_2 budget in line with a particular temperature limit (Friedlingstein *et al.*, 2014; Rogelj *et al.*, 2016) (on average by about 15%). For a greater than 66% chance of limiting temperature rise to below 2°C relative to preindustrial levels, the most appropriate carbon budget estimate was suggested to be 590-1240 $GtCO_2$ from 2015 onwards (Rogelj *et al.*, 2016). The variation of CO_2 budgets within this range depends on the non-CO_2 contribution to overall temperature rise at the time of peak warming. A study on the influence of non-CO_2 forcers on CO_2 budgets found a relative small influence of black-carbon and sulphate aerosol mitigation on CO_2 budgets of about ±5% (Rogelj *et al.*, 2015b). However, the success or failure of methane and hydro-fluorocarbon (HFC) mitigation would influence CO_2 budgets significantly, with variations of up to 60% for the remaining CO_2 budget over the 21st century (Rogelj *et al.*, 2015b). Furthermore, further research has highlighted which energy system transitions are required for staying within a specific CO_2 budget (van Vuuren *et al.*, 2016). For example, scenarios with a CO_2 budget of less than 1000 $GtCO_2$ generally supply between 50-75% of global primary energy demand in 2050 with low-carbon technologies,[4] compared to less than 20% supplied by these technologies today (van Vuuren *et al.*, 2016). Finally, a recent study also showed how CO_2 budgets are influenced by seemingly unrelated mitigation technology choices (Rogelj *et al.*, 2015c) .For example, if specific CO_2 mitigation technologies like carbon capture and storage (CCS) are excluded from the portfolio of mitigation options, CO_2 mitigation might become more expensive and if all greenhouse gases are reduced in a basket approach that allows for trading between different greenhouse gases, more non-CO_2 emissions will be reduced in relative terms. This results in a lower non-CO_2

[4] Low-carbon technologies in this study included all non-fossil energy forms.

contribution to peak warming and therewith a larger compatible CO_2 budget for the same temperature limit (Rogelj *et al.*, 2015c).

3.4 Research Questions and Planned Activities

The concepts and physical basis of CO_2 budgets has been well-established by and since the IPCC AR5. Planned and on-going research is further deepening this understanding and aims at:

- More precise or updated estimates of the remaining CO_2 budget for limiting global mean temperature rise to below 1.5°C or 2°C relative to pre-industrial levels, in light of the climate response and observed historical temperatures.

Better understanding the reversibility of the climate system. A dedicated overshoot scenario has been included in the ScenarioMIP exercise of CMIP6 (O'Neill *et al.*, 2016; Eyring *et al.*, 2016).

4. Differences Between 1.5°C and 2°C Pathways

The previous section explained how one estimates physical limits within which global emissions have to be kept for limiting warming to below 1.5°C or 2°C. In a next step, integrated emission scenarios can help understand how these budgets can be spread and used over time, taking into account how our energy system and society can transform itself. A key question arising from the Paris Agreement's long-term temperature goal is now how emissions pathways leading to limit warming to 1.5°C or 2°C compare. As highlighted earlier, the precise definition of 1.5°C or 2°C pathways can strongly influence the associated mitigation requirements. However, this precise definition of the Paris Agreement long-term temperature goal is not a scientific but a political question.

4.1 General Global Pathway Characteristics

Several studies and reports provide either directly or indirectly information about the general characteristics of global pathways for limiting global mean temperature increase to 1.5°C. These characteristics are useful to assess whether current emissions projections are already putting us on a track consistent with 1.5°C. IPCC AR5 reported only to a limited extent on the characteristics of 1.5°C pathways (IPCC, 2014a, c). Based on scenarios that were available in the literature (Luderer *et al.*, 2013; Rogelj *et al.*, 2013a; Rogelj *et al.*, 2013b) it reported that scenarios that have at least 66% probability of limiting warming to below 1.5°C by 2100 (after peaking earlier in the century) are characterized by atmospheric greenhouse gas concentrations below 430 ppm CO_2 equivalent in 2100 and cumulative CO_2 emissions of 680-800 $GtCO_2$ for the 2011-2050 period and between 90-310 $GtCO_2$ for the 2011-2100 period. To stay within these budgets, global CO_2-eq[5] emissions are reduced by 70-95% and 110-120% below 2010 levels in 2050 and 2100, respectively.

Subsequently, a dedicated review of the 1.5°C scenario literature was published (Rogelj *et al.*, 2015a), and other reports, like the UNEP Emissions Gap Report (UNEP, 2015) and the UNFCCC 'Synthesis Report on the Aggregate Effect of Intended Nationally Determined Contributions' (UNFCCC, 2016), have provided more specific information about 1.5°C scenarios. Each of these publications shows information from subsets of the 1.5°C scenarios available in the literature (Luderer *et al.*, 2013; Rogelj *et al.*, 2013a; Rogelj *et al.*, 2013b), for example, by grouping scenarios based on the assumed start year of globally coordinated mitigation action, either 2010 or 2020. Most of the remainder of this section will also be based on insights from these studies.

With a very limited CO_2 budget available, global emission pathways in line with limiting warming to 1.5°C or 2°C relative to pre-industrial levels, steeply decline their global emissions over the coming decades until mid-century. This is illustrated in Figure 3 below. Scenarios which manage to return global mean temperature increase to below 1.5°C in 2100 with greater than 50% probability peak global CO_2 and total greenhouse gas emissions before 2020. There are no scenarios available in the literature which peak later and are still consistent with the 1.5°C definition provided above. This is quite similar for scenarios that limit global mean temperature increase to below 2°C with greater than 66% probability during the entire 21st century. Figure 3 gives an overview of emissions ranges of scenarios in line with various interpretations of 1.5°C and 2°C goals.

Several caveats have to be considered when using the values provided in Figure 3. First, the scenarios underlying these ranges simulate or project global emission pathways that stay within a specific carbon budget or achieve a specific climate target at the lowest cost. That means that emissions reductions are spread over time and over regions in a way such that overall discounted costs are minimized at a global scale. These are not the only scenarios possible. Some possible variations are already included in the ranges provided in Figure 3, like varying the timing when globally coordinated mitigation action starts (2010, 2020, or 2030) or varying which mitigation technologies are available (for example, excluding nuclear power as a mitigation option). However, the scenario set on which Figure 3 is based has not been designed to consistently and evenly span all dimensions for all subsets. A good illustration of this is that the number of models that provide information for each of the categories shown in Figure 3 varies. However, in this case, this variation is the result of arbitrary model sampling which increases the uncertainty of the emission estimates and should not be over-interpreted. This arbitrary sampling bias can be avoided by designing specific experiments in which a set of models attempts to produce well-defined scenarios that answer a pre-defined question. Examples of such experiments broadly related to the 2°C goal of the Cancun Agreement have been published in the literature exploring the influence of near-term action in line with the Durban Platform (Kriegler *et al.*, 2013), the influence of the (un-)availability of key mitigation technologies (Kriegler *et al.*, 2014), or the influence of delayed action until 2030 in combination with technology limitations (Riahi *et al.*, 2015) and the staged accession of countries to a global mitigation framework (Kriegler *et al.*, 2015). While these studies have

[5] CO_2 equivalence in the IPCC AR5 was computed using 100-year Global Warming Potentials (GWP-100) reported in the IPCC Second Assessment Report.

not explicitly assessed the Paris Agreement long-term temperature goals, their insights can be qualitatively re-interpreted in light of the new policy context.

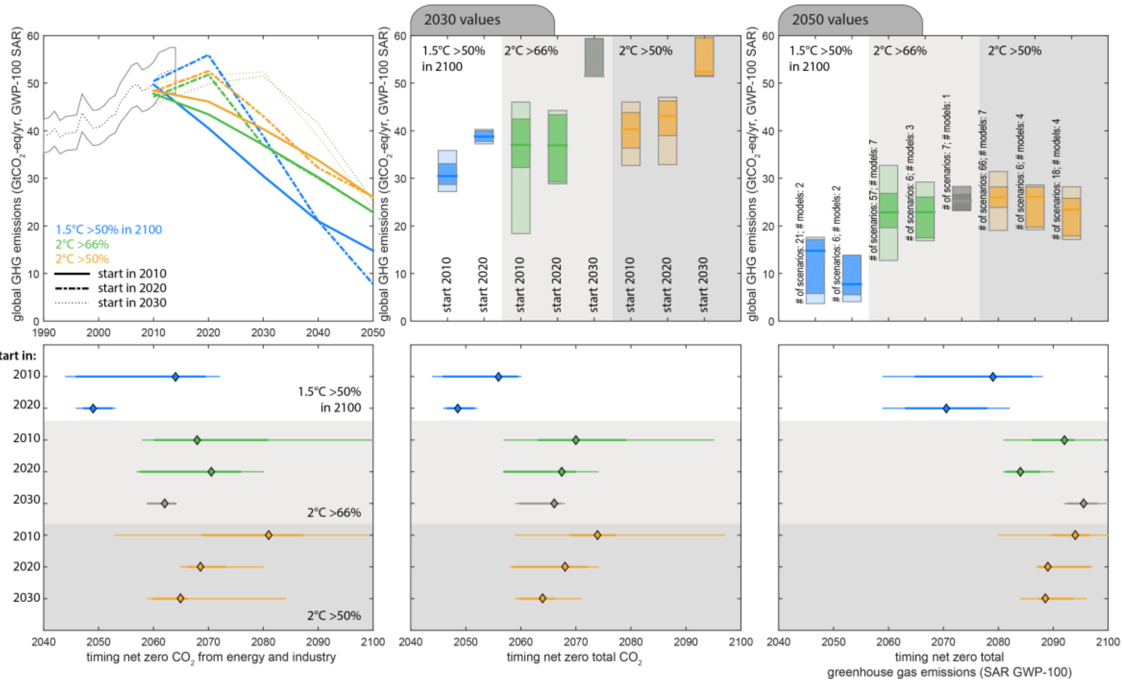

Figure 3 Global emissions pathways and timing of global emission becoming zero. Blue features represents scenarios which hold warming to below 2°C with >66% probability during the entire century and return warming to below 1.5°C with >50% probability in 2100. Green features represent scenarios which hold warming to below 2°C with >66% probability during the entire century but end up with a temperature increase larger than 1.5°C with >50% probability in 2100. Orange features represent scenarios which hold warming to below 2°C with 50-66% probability during the entire century. Scenarios are further grouped depending on the timing at which globally coordinated mitigation action is assumed to start (2010, 2020, or 2030). The number of available scenarios per category and the number of contributing modelling frameworks are provided in the top right panel. Categories for which robustness is strongly questionable are shaded grey. Scenarios are from the IPCC AR5 Scenario Database (hosted at IIASA and available at: tntcat.iiasa.ac.at/AR5DB/) and Rogelj et al. (2015a).

4.2 Key Insights from Like-with-like Comparison

The ranges shown in Figure 3 are based on so-called “ensembles of opportunity” – an arbitrary selection of scenarios that happen to be available. Additional insights, however, can be derived from a dedicated like-with-like comparison: the comparison of two scenarios which are identical in all aspects but the stringency of climate mitigation action. Such an approach allows to identify key areas in which 1.5°C scenarios differ from 2°C scenarios.

IPCC AR5 already reported that 1.5°C scenarios[6] are characterized by *“immediate mitigation action; the rapid upscaling of the full portfolio of mitigation technologies; and development along a low-energy demand trajectory”* (IPCC, 2014c). A later study (Rogelj *et al.*, 2015a) has

[6] In this context assumed to keep global mean temperature increase to below 1.5°C in 2100 with greater than 66% probability, while allowing temperature increase to exceed the 1.5°C limit earlier during the 21st century.

identified further key differences between scenarios that keep global mean temperature increase to below 2°C with at least 66% probability and scenarios that additionally manage to limit temperature increase to below 1.5°C in 2100 with at least 50% probability, temporarily exceeding 1.5°C during the 21st century. This study reported that such 1.5°C scenarios require a full portfolio of mitigation options, and are characterized by:

- ***Comprehensive emission reductions over the 2015-2025 time period***. Diverting investments from fossil-fuel infrastructure to low-carbon developments is critical over this period. All available scenarios in line with 1.5°C by 2100 peak global greenhouse gas emissions by 2020 at the latest.
- ***CO_2 reductions beyond global net zero in order to peak and decline temperatures***. Because the assessed 1.5°C scenarios temporarily exceed the 1.5°C limit with greater than 50% probability during the 21st century, they peak median temperatures during the 21st century above 1.5°C and then decline them again later to below 1.5°C in 2100. They thus initially overspend the allowable 1.5°C CO_2 budget. This requires CO_2 to be removed actively from the atmosphere at a later point in time. The assessed 1.5°C scenarios reach net zero CO_2 emission around mid-century, which is about 10 to 20 years earlier than in 2°C scenarios that keep temperatures to below 2°C with a greater than 66% probability.
- ***The additional emission reductions mainly come from CO_2***. The study found that the non-CO_2 greenhouse gas mitigation potential is often already fully used in the assessed 2°C consistent scenarios. The remaining non-CO_2 emissions are from activities for which very limited mitigation options have been identified, like from certain agricultural practices.
- ***The energy supply system is rapidly and profoundly decarbonised in the near term***. The additional CO_2 reductions mentioned earlier, are achieved through early reductions in the power sector.

Reducing demand in hard-to-decarbonize sectors. This is the case in the industry, buildings and transport sectors. These demand reductions can also be induced by climate policy. ***Increasing energy efficiency is crucial***. The study reports that most 1.5°C scenarios need to assume that energy use per unit of economic output decreases at a faster pace than historically observed.

The same study also reports that mitigation costs are higher in 1.5°C scenarios. For example, aggregated long-term mitigation costs can be up to a factor 2 higher in 1.5°C scenarios than in corresponding 2°C scenarios (the precise interpretation of these climate targets was described above). Importantly, such cost estimates ignore the potentially significant benefits of avoided climate damages and co-benefits of improved local health and mobility. Studies have shown that taking into account the monetary value of these co-benefits can rapidly exceed the initial mitigation costs (West *et al.*, 2013).

4.3 Research Questions and Planned Activities

The literature available on scenarios that limit global mean temperature increase to below 1.5°C by the end of the century has identified important contributions of negative emissions: the active removal and permanent storage of CO_2 from the atmosphere. Several technologies have been suggested which could deliver such negative emissions (Smith *et al.*, 2016;

Williamson, 2016). Current scenarios, however, mainly make use of a technology referred to as BECCS, the combination of bio-energy power production with carbon capture and storage. This technology is preferred by models because it provides negative emissions while at the same time generating power, lowering its overall operational cost. However, there are important sustainability concerns related to large-scale bio-energy production, in particular as biomass production can compete with agriculture and natural ecosystems over water and land (Slade *et al.*, 2014; Creutzig *et al.*, 2015; Bonsch *et al.*, 2016). At present, the scenario literature does not provide conclusive evidence that 1.5°C scenarios would require more bio-energy deployment than 2°C scenarios (Schleussner *et al.*, 2016). These issues are very important in the wider context of sustainable development and require urgent clarification.

Further key research questions are related to the policies and other key enabling factors which can induce the rapid and potentially disruptive transformations required in stringent mitigation scenarios in line with 1.5°C and 2°C. For example, scenario studies have highlighted the key importance of energy efficiency improvements and demand reductions for the achievability of the Paris Agreement long-term temperature goal. Even if such measures and transitions would already make economically sense in a world without climate change mitigation they are not taking place yet. Research which draws on empirical sources, systems understanding and social science is critical to make progress in this area (Geels *et al.*, 2016).

Several research activities are currently attempting to expand the literature base of scenarios that limit global mean temperature rise to below 1.5°C by 2100. For example, both in the framework of the Shared Socioeconomic Pathways (SSPs) (Riahi *et al.*, in press) and on-going research projects (for example, http://www.fp7-advance.eu/) have started activities which aim at providing insights on the issue of 1.5°C from a wider range of models.

5. Balance by Sources and Removals by Sinks

Article 4 of the Paris Agreement indicates that Parties will aim at achieving a *“balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century […]”* (UNFCCC, 2015b). Also here some issues are still left open for interpretation. Here, we will look at this statement through a scientific lens and deduce interpretations which are consistent with the Paris Agreement long-term temperature goal and the scientific literature.

Article 4 can be tied back to statements from and findings based on the IPCC AR5. First, the existence of a finite CO_2 budget for stabilizing global mean temperature increase (IPCC, 2013) implies that global CO_2 emission *have* to become zero at some point (Knutti and Rogelj, 2015). This is a requirement for stabilizing temperature rise at any level, not just ‘well below 2°C’ or 1.5°C. Moreover, IPCC also reported that pathways which limit global mean temperature rise to below 2°C with greater than 66% probability require substantial emission reductions of the coming decades and near zero emissions of CO_2 and other long-lived greenhouse gases by the end of the century (IPCC, 2014b). The Paris Agreement’s Article 4, however, refers to the second half of the century and all greenhouse gases, which makes it more consistent with the more stringent long-term temperature goal in Article 2.

Achieving a balance between emissions and removals can be translated in scientific terms as achieving net zero greenhouse gas emissions globally. From a scientific point of view, Article 4 thus makes most sense at a global scale, although also at the single country level net zero emissions will have to be achieved, although timing and extent of this will most likely vary depending on the mitigation potential available. In order to assess when net greenhouse gas emissions are balanced, emissions from different greenhouse gases have to be translated into CO_2-equivalence in order to make them comparable (Fuglestvedt *et al.*, 2003). Generally, Global Warming Potentials over a 100-year time period (GWP-100) are used, but other metrics are also available, see (Myhre *et al.*, 2013). Other metrics can come with both advantages and disadvantages. Advantages are often that they can provide equivalence metrics which are more closely linked to the actual temperature impact of emissions over a given time period instead of the forcing. An example of this are global temperature potentials or GTPs (Shine *et al.*, 2005). The disadvantage for this particular alternative metric is that the relationship between emissions and temperatures in more uncertain than the relationship between emissions and their radiative forcing effect, adding to the overall uncertainty of the metric.

The choice of this metric is important in combination with the time dimension provided in Article 4 of the Paris Agreement (i.e., "in the second half of this century"). Based on scenarios from the IPCC AR5 Scenario Database and the recent literature (Rogelj *et al.*, 2015d), Figure 3 shows that achieving net zero GWP-100-weighted greenhouse gas emissions in the second half of this century is consistent with limiting warming below 2°C, leaving the option to limit warming by 2100 to below 1.5°C. Achieving net zero greenhouse gas emissions is not a sufficient condition though, to limit warming to well below 2°C. This is illustrated in Figure 4, which shows that in some scenarios which reach zero globally aggregated greenhouse gas emissions in the last quarter of this century temperature increase reaches 2.5°C relative to pre-industrial levels. Choosing a different metric here would change the relative contribution of various greenhouse gases and therewith the perceived timing of when net zero greenhouse gas emissions are achieved. Changing the CO_2-equivalence metric from GWP-100 to any other metric could hence potentially introduce an internal inconsistency between the Paris Agreement's Articles 2 and 4. Any change in CO_2-equivalence metric should thus be considered in conjunction with the additional information and context provided in these Articles.

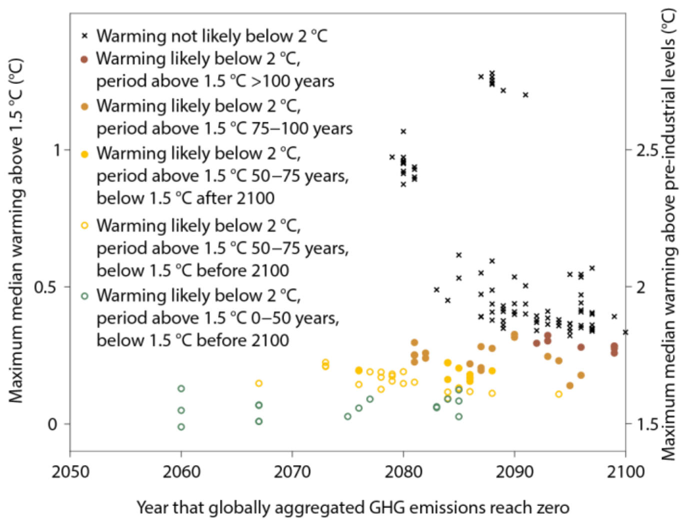

Figure 4 **Relationship between the years that globally aggregated greenhouse gas emissions (aggregated with SAR GWP-100) reach zero and maximum median warming above pre-industrial levels. Figure adapted from Schleussner *et al*. (2016).**

An additional issue is related to whether sinks which are not of anthropogenic origin can be included in achieving this balance. The scientific concepts which link the stabilisation of global mean temperature rise to anthropogenic greenhouse gas emissions, indicate that only emissions and removals of anthropogenic origin should be included in this equation. If anthropogenic sources and sinks of CO_2 are balanced, global mean temperatures do not rise any further but stabilize. If a balance is achieved between anthropogenic sources and sinks of all greenhouse gases, global mean temperatures would first stabilize, after which they would potentially slowly start to decline as negative CO_2 emissions compensate for residual non-CO_2 emissions from hard to mitigate sectors like agriculture. On the other hand, if natural ocean or terrestrial carbon sinks are also included in achieving this balance, temperatures would not stabilize, only climate forcing would. Temperatures would continue to rise from their transient state into equilibrium. Earlier research has shown that this results in additional warming (Hansen *et al.*, 2005), and IPCC reports that this additional warming can be about 20-30% of the temperature increase at the time of stabilizing radiative forcing (Stocker *et al.*, 2013).

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