OECD Environment Working Papers No. 222

Paris-consistent climate change mitigation scenarios: A framework for emissions pathway classification in line with global mitigation objectives

Coline Pouille, Marcia Rocha, Jolien Noels, Raphaël Jachnik

https://dx.doi.org/10.1787/0de87ef8-en

OECD

Research Collaborative
Tracking Finance for Climate Action

Organisation for Economic Co-operation and Development

ENV/WKP(2023)14

For Official Use **English - Or. English**

26 September 2023

ENVIRONMENT DIRECTORATE

Paris-consistent climate change mitigation scenarios: A framework for emissions pathway classification in line with global mitigation objectives

Environment Working Paper No. 222

By Coline Pouille (1), Marcia Rocha (1), Jolien Noels (1) and Raphaël Jachnik (1)

(1) OECD Environment Directorate

Authorised for publication by Jo Tyndall, Director, Environment Directorate

Keywords: Climate change mitigation scenarios, greenhouse gas emissions pathways, net zero targets, Paris Agreement alignment, 1.5°C temperature goal, temperature overshoot.

JEL Codes: Q54, Q56, C68.

Contacts:
Coline Pouille (coline.pouille@oecd.org)
Marcia Rocha (marcia.rocha@oecd.org)
Jolien Noels (jolien.noels@oecd.org)
Raphaël Jachnik (raphael.jachnik@oecd.org)

JT03527281

OECD ENVIRONMENT WORKING PAPERS

OECD Working Papers should not be reported as representing the official views of the OECD or of its member countries. The opinions expressed and arguments employed are those of the author(s). Working Papers describe preliminary results or research in progress by the author(s) and are published to stimulate discussion on a broad range of issues on which the OECD works.

This series is designed to make available to a wider readership selected studies on environmental issues prepared for use within the OECD. Authorship is usually collective, but principal author(s) are named. The papers are generally available only in their original language – English or French – with a summary in the other language.

Comments on Working Papers are welcomed, and may be sent to:

OECD Environment Directorate

2 rue André-Pascal, 75775 Paris Cedex 16, France

or by email: env.contact@oecd.org

OECD Environment Working Papers are published on

www.oecd.org/environment/workingpapers.htm as well as

on the OECD iLibrary (www.oecdilibrary.org)

Abstract

Since the adoption of the Paris Agreement, governments and economic actors have increasingly been setting greenhouse gas emissions reduction or net-zero targets. Amidst risks of delayed action and greenwashing, there is need to understand whether climate-related targets and transition plans are consistent with the Paris Agreement. Climate change mitigation scenarios can be used as inputs to design such targets and plans, and as benchmarks to assess progress towards them. In this context, this paper proposes criteria for selecting global climate change mitigation scenarios that can be considered consistent with the Paris Agreement temperature goal and emissions objectives, based on state-of-the-art literature on climate science and mitigation scenarios.

The analysis applies the proposed criteria to identify envelopes of Paris-consistent scenarios among global climate change mitigation scenarios in the Intergovernmental Panel on Climate Change Sixth Assessment Report scenarios database. The analysis demonstrates that a rigorous science-based approach that considers all mitigation-related objectives in the Paris Agreement is necessary to identify Paris-consistent global scenarios. This in turn is critical for understanding near-term implications of long-term climate targets, in light of the need for steep emissions reductions in the coming decade to limit overshoots of 1.5°C and associated climate risks.

Keywords: Climate change mitigation scenarios, greenhouse gas emissions pathways, net zero targets, Paris Agreement alignment, 1.5°C temperature goal, temperature overshoot.

JEL Codes: Q54, Q56, C68.

Résumé

Depuis l'adoption de l'Accord de Paris, les acteurs gouvernementaux et économiques sont de plus en plus nombreux à fixer des objectifs de réduction des gaz à effet de serre ou de neutralité nette. Face aux risques de retard dans l'action climatique et d'écoblanchiment, il est nécessaire de comprendre si les objectifs et plans de transition climatiques sont cohérents avec l'Accord de Paris. Les scénarios d'atténuation du changement climatique peuvent servir de base à l'élaboration de ces objectifs et plans, et de référence pour évaluer les progrès. Dans ce contexte, ce document propose des critères pour sélectionner des scénarios mondiaux d'atténuation du changement climatique qui peuvent être considérés comme cohérents avec les objectifs de température et d'émissions de l'Accord de Paris, en se fondant sur la littérature en science du climat et les scénarios d'atténuation les plus récents.

L'analyse applique les critères proposés pour identifier des enveloppes de scénarios compatibles avec l'Accord de Paris, parmi les scénarios mondiaux d'atténuation du changement climatique recueillis dans la base de données des scénarios du sixième rapport d'évaluation du Groupe d'experts intergouvernemental sur l'évolution du climat. L'analyse démontre qu'une approche scientifique rigoureuse prenant en compte tous les objectifs liés à l'atténuation de l'Accord de Paris est nécessaire pour identifier les scénarios mondiaux compatibles avec l'Accord. Cela est essentiel pour comprendre les implications à court terme des objectifs climatiques long-terme, compte tenue de le nécessité de réductions significatives des émissions dans la prochaine décennie pour limiter les dépassements de 1.5°C de réchauffement mondial et les risques climatiques associés.

Mots-clés: Scénarios d'atténuation du changement climatique, trajectoires d'émissions de gaz à effet de serre, objectifs de zéro émission nette, alignement avec l'Accord de Paris, objectif de 1.5°C de réchauffement climatique, dépassement temporaire du seuil de 1.5°C.

Codes JEL: Q54, Q56, C68.

Acknowledgments

This work is the result of a collaboration between the Climate, Biodiversity and Water (CBW) division (Climate Quantitative Assessments team), and the Finance, Investment and Global Relations (FIG) division (Finance for Climate Action team) within the OECD Environment Directorate. The paper was authored by Coline Pouille, Marcia Rocha, Jolien Noels and Raphaël Jachnik, under the supervision of Walid Oueslati, Acting Head of the CBW Division and Krzysztof Michalak, Acting Head of the FIG Division.

This work is part of the Programme of Work and Budget of the OECD Environment Policy Committee (EPOC) on both climate change mitigation and sustainable finance. The analysis contributes to the body of work of the Research Collaborative on Tracking Finance for Climate Action, an OECD-led technical research platform to advance and share knowledge for improving the tracking and assessment of climate-relevant finance, including to inform finance-related discussions under the United Nations Framework Convention on Climate Change (UNFCCC).

The study benefited from:

- Feedback, comments and/or suggestions from OECD colleagues: Aimée Aguilari Aber, Joseph Cordonnier, Jane Ellis, Chiara Falduto, Sirini Jeudy-Hugo, Elisa Lanzi, Michael Mullan, Deger Saygin, Toon Vandyck.
- Oral feedback and written comments from delegates to the OECD Working Party on Climate, Investment and Development (WPCID) on both an initial scoping note and a complete draft.
- Review and feedback from external climate scientists and experts: Franck Lecocq (Centre International de Recherche sur l'Environnement et le Développement), Joeri Rogelj (Imperial College London), Ben Sanderson (Center for International Climate Research), Carl-Friedrich Schleussner (Climate Analytics).

Table of contents

Tables

Figures

Boxes

Glossary

Climate change mitigation scenario: the coherent set of modelled quantitative pathways showing how to achieve a given climate goal. Depending on their complexity, climate change mitigation scenarios may include internally consistent pathways for hundreds of different variables, such as for the evolution over time of emissions by gas, energy use, energy supply, land use, economic and sectoral variables etc.

Emissions pathway: the modelled trajectory of anthropogenic emissions for a specific gas (e.g. carbon dioxide) or for aggregated GHG, that is part of a scenario. For greater clarity, this paper restricts the use of the term pathway to this definition, acknowledging, however, that the term is often employed more generally in reference to a complete mitigation scenario.

Scenario envelope: a set of several scenarios selected based on a criterion or on several criteria. For example, all scenarios consistent with a specific temperature outcome form an envelope of scenarios.

Global warming: the increase in global mean surface temperature (GMST), relative to the reference period 1850-1900.

Overshoot: the temporary exceedance of a given global warming limit, in general 1.5°C. Overshoot implies that global temperatures peak and then decline thanks to global negative net emissions.

Likelihood of staying below a temperature: the chance that a given scenario or carbon budget gives to remain below a given level of global warming, such as 1.5°C, throughout the century. Indeed, the temperature outcome associated with an emissions pathway or a carbon budget is estimated probabilistically.

Kyoto GHG gases: the set of greenhouse gases (GHG) covered by the Kyoto Protocol and whose emissions are usually modelled in climate change mitigation scenarios. These include mainly carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4), as well as sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). Total GHG emissions in CO_2 equivalent terms aggregate these Kyoto gases, weighing them in general by their global warming potentials.

Net-zero CO_2 emissions: a state where anthropogenic CO_2 emissions are balanced by anthropogenic CO_2 removals over a given period of time (e.g. over a year). The concept of net-zero emissions is only used at the global scale in this paper.

Net-zero GHG emissions: net-zero emissions are achieved when metric-weighted anthropogenic emissions of greenhouse gases to the atmosphere are balanced by metric-weighted anthropogenic removals over a given period of time (e.g. over a year). Given that multiple greenhouse gases are involved, the quantification of net-zero GHG emissions depends on the metric chosen to aggregate emissions of different gases. In this paper, the metric used is Global Warming Potentials over 100 years (GWP_{100}) as estimated by the IPCC AR6. Indeed, under the Paris Rulebook (Decision 18/CMA.1, annex, paragraph 37), parties have agreed to use GWP_{100} values from the IPCC AR5 or from a subsequent IPCC Assessment Report to report aggregate emissions and removals of GHGs.

Sources: (IPCC, 2018[1]; IPCC, 2021[2]; IPCC, 2022[3]).

Executive summary

Since the adoption of the Paris Agreement, governmental, business, financial, and other economic actors have increasingly been setting greenhouse gas (GHG) reduction or net-zero targets and transition plans. Amidst evidence of delayed action and greenwashing, there is growing need to understand whether these targets and related transition plans are consistent with the Paris Agreement's mitigation-related objectives, as well as promote increased transparency and accountability. The Paris Agreement adopted in 2015 is the main guiding policy framework for global climate action and includes both a global long-term temperature goal (Article 2.1a) and a long-term emissions objective (included in Article 4). While providing "a direction of travel", the formulations of Article 2.1a and 4 are subject to some degree of interpretation in terms of translation into future emissions.

The aim of this paper is to propose an approach for identifying global climate change mitigation scenarios that can be considered consistent with the Paris Agreement's long-term temperature goal and emissions objectives. Global climate change mitigation scenarios play a key role in formulating targets consistent with the ambition of the Paris Agreement and for measuring the alignment of transition plans and policy pledges with the Paris Agreement's mitigation ambition. This paper explores options for interpreting and translating the Paris Agreement's long-term temperature goal and emissions objective into a set of potential concrete criteria to select Paris-consistent global climate change mitigation scenarios. The aim is to contribute to an enhanced use of such scenarios by economic actors setting net-zero targets, developing transition plans and assessing alignment with the Paris Agreement.

This paper focuses on consistency with the Paris Agreement at the global level, while recognising that downscaling global scenarios to a more granular geographic level is needed for them to serve as reference in assessments by individual governmental and economic actors. The geographical downscaling of global pathways is challenging as it requires burden-sharing assumptions and principles (e.g., based on historical responsibility or capacity), which fall outside the scope of this paper. It is, however, important to note that global climate change mitigation scenarios such as those explored in this paper are currently used as inputs for target setting and Paris alignment assessment methodologies, notably in the financial and corporate sectors.

Based on considerations from recent findings in climate change mitigation scenarios and broader climate research, the paper proposes a set of five criteria for selecting global climate change mitigation scenarios that can be considered as Paris-consistent (Table 1). Two possible sets of criteria are proposed, corresponding to two different levels of stringencies in the interpretation of the Paris Agreement's mitigation-related objectives. Applying the criteria to filter the 1,200 scenarios gathered in the IPCC AR6 scenarios database yields two envelopes of 26 (stringent interpretation) and 55 (less stringent interpretation) Paris-consistent scenarios respectively.

Table 1. Criteria for selecting global scenarios consistent with the Paris Agreement's mitigation-related objectives

<table>
<tr><th rowspan="2">Paris Agreement Article</th><th rowspan="2">Paris Agreement mitigation goal and objectives</th><th colspan="2">Criteria</th></tr>
<tr><th>More stringent interpretation</th><th>Less stringent interpretation</th></tr>
<tr><td>2.1a</td><td>"pursuing efforts to limit the temperature increase to 1.5 °C"</td><td colspan="2">Criterion 1
1.5°C in 2100
In 2100, the scenario must hold global warming[1] below 1.5°C with at least 50% chance[2].

Criterion 2
no or limited overshoot of 1.5°C
Throughout the century, the scenario must hold global warming below 1.6°C with 50% chance.</td></tr>
<tr><td>2.1a</td><td>"holding the increase in global average temperature to well below 2 °C"</td><td>Criterion 3
well-below 2°C throughout the century
Throughout the century, the scenario must hold global warming below 2 °C with at least 90% chance.</td><td>Criterion 3
well-below 2°C throughout the century
Throughout the century, the scenario must hold global warming below 2 °C with at least 78.3% chance.</td></tr>
<tr><td>4.1</td><td>"aim to reach global peaking of greenhouse gas emissions as soon as possible
[…and] achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century"</td><td>Criterion 4
peak GHG emissions
The scenario must ensure that global GHG emissions[3] peak at or before 2025.

Criterion 5
net-zero GHG emissions
The scenario must achieve global net-zero GHG emissions before 2100.</td><td>Criterion 4
peak GHG emissions
The scenario must ensure that global GHG emissions peak at or before 2030.

Criterion 5
near net-zero GHG emissions
The scenario must achieve global net-zero CO_2 emissions before 2100, with residual net GHG emissions of 5 Gt or less in 2100.</td></tr>
<tr><td colspan="2">Number of scenarios in the IPCC AR6 database</td><td>26</td><td>55</td></tr>
</table>

The combination of five criteria highlights the need for a precautionary approach in selecting climate change mitigation scenarios used as benchmarks to inform targets, plans and actions by governmental, business, financial and other economic actors. This paper recognises that more lenient interpretations of the Paris Agreement's provisions than the ones herein presented are possible. However, such lenient interpretations overlook the overwhelming evidence on climate change and its impacts, notably the crossing of climate system tipping points. It is important to note that the criteria proposed in this paper and the resulting emissions envelopes reflect the most recent science and scenarios as of 2023. This is, however, a dynamic field. The criteria and envelopes would thus need to be updated over time to ensure that they encompass the latest scientific evidence on climate risks and emissions scenarios, as well as relevant political, societal and technological developments. It is additionally important to note that mitigation scenarios can become outdated simply because they diverge from real world emissions.

Failing to look at all the criteria simultaneously may lead users to select scenarios that are not or only partly consistent with the long-term temperature goal and emissions objectives of the Paris

---

[1] Increase in global mean surface temperature (GMST), relative to the reference period 1850-1900. See Glossary for full definition of the use of this term in this paper.

[2] See Glossary for a definition of the likelihood of staying below a given temperature.

[3] GHG emissions are calculated using Global Warming Potentials over 100 years (GWP_{100}). See Glossary for full definitions of the concepts of GHG emissions, net-zero GHG and net-zero CO_2 as used in this paper.

Agreement. The scenario envelopes in this paper are derived by applying all criteria for Paris-consistency from Table 1. They represent less than 4% and 8%, for the more and less stringent sets of criteria respectively, of all scenarios in the AR6 database that keep global warming below 2°C with a 50% chance throughout the century. In contrast, a partial consideration of the Agreement's carefully-negotiated language may fail to avoid the dangerous levels of climate change the Paris Agreement was created to avoid. Indeed, common approaches considering only portions of the mitigation objectives (e.g. "net zero by 2050", "1.5°C in 2100", or "well-below 2°C" only) result in the selection of a larger number of less ambitious scenarios. For example, nearly half of the IPCC AR6 database scenarios are "likely below 2°C," and many scenarios that reach net-zero carbon dioxide (CO_2) emissions by 2050 do not limit warming to 1.5°C.

The criteria framework put forward in this paper can be used by various governmental and economic actors for identifying and selecting Paris-consistent climate change mitigation scenarios to serve as inputs to setting credible GHG reduction targets and transition plans, as well as to assessing progress towards alignment with the Paris Agreement. A first practical application of this criteria framework, presented in the OECD paper "Climate change mitigation scenarios for financial sector target setting and alignment assessment: A stocktake and analysis of their Paris consistency, practicality, and assumptions", shows that most of the global scenarios currently used in the financial sector for the purpose of climate-related target setting and alignment assessments do not fulfil all five criteria of Paris consistency. This separate paper explores further dimensions relating to the applicability of such scenarios (notably in relation to geographical and sectoral granularity), as well as their plausibility (in terms of underlying assumptions and mitigation strategies).

Based on the selected Paris-consistent scenario envelopes, the present paper also identifies good practices to improve and strengthen GHG emissions reduction and net-zero targets of all types of stakeholders, as set out below:

- Emissions reduction targets should cover all individual Kyoto gases, in addition to CO_2 and aggregated GHG emissions.
- Targets labelled as "net zero" need to be set for reaching not only net-zero CO_2 emissions, but also net-zero total GHG emissions later in the century.
- In addition to setting a timing for reaching net-zero GHG emissions, it is crucial that targets encompass interim emissions reductions targets for early and deep emissions reductions by 2030 and further steep reductions by 2040, to limit dangerous overshoots of 1.5°C.

The Paris-consistent scenario envelopes derived in this paper could also inform policy strategies and plans for achieving the net-zero transition and help guide climate policy decisions in the short and medium-term to implement the Paris Agreement. Indeed, the envelopes can deliver insights on the short- and medium-term mitigation action required across the energy, transport, buildings, agricultural and land use systems to reach the long-term Paris temperature goal and emissions objectives. These insights can provide guidance on the formulation of national short-term and mid-term strategies for the low carbon transition. Transition benchmarks based on the envelopes can also be compared against national and global indicators to track progress of the transition.

1 Introduction

The Paris Agreement adopted in 2015 is the main guiding policy framework for global climate ambition and action. It includes two key climate change mitigation objectives: (i) a global long-term temperature goal of "holding the increase in 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"; and (ii) an emissions objective to "reach global peaking of greenhouse gas emissions as soon as possible […and] to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (UNFCCC, 2015[4]).

Climate change mitigation scenarios[4] are playing an increasing role in operationalising the Paris Agreement and in transitions to net zero (Guivarch et al., 2022[5]). They are currently used by a wide range of stakeholders, including governments, private companies and the financial sector, to assess alignment with global Paris climate mitigation ambition and to set net-zero targets. By making the link between long-term global warming and emissions pathway, they serve as global ambition benchmarks for understanding the ambition gap between national targets and pledges put forward in nationally determined contributions (NDCs) on the one hand, and global Paris Agreement goals on the other hand. Measuring the ambition gap relies on estimating future emissions implied by NDCs (Meinshausen et al., 2022[6]), and comparing these with Paris-consistent emissions pathways; this exercise is undertaken in particular in the UNEP's emissions gap report (UNEP, 2022[7]) and the IPCC AR6 report (Lecocq et al., 2022[8]). The private and financial sectors are also increasingly using these scenarios to measure alignment of investments and corporate transition plans with the Paris Agreement (Noels and Jachnik, 2022[9]).

The primary aim of this paper is to define climate change mitigation scenarios that are in line with the Paris Agreement's long-term temperature goal and emissions objectives, thereby contributing to an enhanced use of such scenarios in net-zero target setting and alignment assessments. The Paris Agreement sets a long-term temperature goal and the objective of reaching net-zero GHG emissions. However, these are not expressed in terms of amount of GHG emissions *per se*. Further, they do not explicitly define important aspects of future emissions pathways, such as timing of peak emissions, a clear timing for achieving net-zero emissions or level and duration of potential overshoots of the temperature goal throughout the century. As a result, while providing "a direction of travel", the formulation of the Paris Agreement's climate mitigation objectives inherently opens to some degree of interpretation in terms of how they translate into future global emissions pathways.

This paper examines ways to translate the Paris Agreement's mitigation objectives into a set of specific criteria that can help identify global climate change mitigation scenarios that are useful for setting decarbonisation targets and for measuring alignment with the Paris Agreement. More specifically, the analysis pursues three specific objectives:

- Highlight challenges and pitfalls in defining alignment with the Paris Agreement mitigation objectives at the scenario level.

[4] See Glossary for full definitions of the use of the terms climate change mitigation scenarios, emissions pathways and scenario envelopes in this paper.

- Identify a set of transparent criteria that can help analyse the consistency of global climate change mitigation scenarios with the Paris Agreement.
- Provide reference envelopes of scenarios consistent with the Paris Agreement, based on the most recent climate change mitigation scenarios literature.

This analysis and the criteria translating the Paris Agreement's long-term temperature goal and emissions objectives are informed by recent findings in climate change mitigation scenarios and in broader climate research. Looking at such recent developments is needed, as it has become clear that different interpretations of the Paris Agreement mitigation objectives could lead to considerably different levels of climate change (Rajamani, 2016[10]; Fuglestvedt et al., 2018[11]; Seneviratne et al., 2018[12]; Rogelj et al., 2019[13]; Armstrong McKay et al., 2022[14]). For example, a long and high overshoot of the 1.5 °C limit could lead to the irreversible crossing of some of the earth's so-called tipping points (Armstrong McKay et al., 2022[14]; OECD, 2022[15]). Such considerations need to inform assessments of consistency with the Paris Agreement, which, beyond its temperature and emissions objectives, also includes a goal of "increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience" (Article 2.1b). The text of the initial Framework Convention also explicitly refers to "prevent[ing] dangerous anthropogenic interference with the climate system" (UNFCCC, 1992[16]).

This paper has the potential to provide a timely contribution to the setting of GHG emissions targets, design of transition plans and assessments of alignment with the Paris Agreement for a wide range of stakeholders. In particular, OECD research has shown that climate change mitigation scenarios are fundamental inputs to climate-alignment assessment methodologies in the financial sector and can drive alignment results for a given financial asset (Noels and Jachnik, 2022[9]). Hence, a first application of the analytical framework and criteria put forward by this paper is conducted, in a parallel paper, in the context of climate-alignment assessments in the financial sector, thereby placing a strong emphasis on the issue of the environmental integrity of such assessments (Noels et al., 2023[17]). This second paper then explores further dimensions relating to the applicability of such scenarios (notably in terms of geographical and sectoral granularity, as well as their plausibility (in terms of underlying assumptions and mitigation strategies).

Climate change mitigation scenarios developed over the past decades attempt to reconcile temperature and emissions objectives, such as the ones formulated in the Paris Agreement, with future developments of the socio-economic system (Riahi et al., 2022[18]). These efforts have been undertaken by the climate change research community (e.g. through recent global consortia of research teams) and by institutional bodies such as the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA). Climate change mitigation scenarios are crucial for much of the analysis undertaken in the IPCC's Assessment reports (IPCC, 2022[19]). Latest IPCC Assessment reports have been accompanied by a scenarios database comprising the latest generation of climate change mitigation scenarios. The most recent of the IPCC scenarios database was made available in the context of the publication of the IPCC's AR6 report (Byers et al., 2022[20]).

The IPCC AR6 scenarios database serves as the backbone for the analysis undertaken in this paper. The database encompasses a set of over 2,000 global scenarios produced by scientific research and institutional communities. It provides a wealth of publicly available and relatively standardised data across many modelling and researcher groups (Riahi et al., 2022[18]). As a result, the database reflects a broad set of mitigation trajectories representing different potential emissions futures and associated temperature outcomes, resulting from a large spectrum of assumptions, notably in terms of socio-economic and technological developments (Byers et al., 2022[20]).

This paper focuses only on consistency with the Paris Agreement at the global climate change mitigation scenario level, while recognising that downscaling scenarios to higher geographical resolution is needed for them to serve as references for assessments by governmental, financial, and other economic actors. The global climate change mitigation scenarios published as part of the IPCC AR6 on which this paper is based are global least-cost scenarios that inform where emission reductions are most cost-efficient to reach global climate goals. Such scenarios are agnostic about who should finance these emissions reductions and how to fairly allocate mitigation efforts across countries and regions. The geographical downscaling of global pathways is challenging because it requires to account for equity considerations. The Paris Agreement notably specifies that its temperature target and adaptation target "will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances" (UNFCCC, 2015[4]). This reflects a concept originally expressed in the 1992 Convention and highlights the importance of developed countries taking the lead on ambitious climate action. Addressing equity requires analytical frameworks encompassing at the same time burden-sharing schemes and principles as well as climate finance considerations (Pachauri et al., 2022[21]), which fall outside of the scope of the present paper. The analysis in this paper focuses on consistency with the Paris Agreement at the global level, which is indeed also a crucial primary step to advance discussions on equity (Ganti et al., 2023[22]).

The remainder of this paper is structured as follows:

- Chapter 2 explores and discusses issues and considerations that are critical for informing an assessment of the consistency of global climate change mitigation scenarios with the global objectives in the Paris Agreement.
- Chapter 3 suggests a criteria framework for selecting climate change mitigation scenarios consistent with the Paris Agreement temperature goal and emissions objectives; it then applies the framework to the AR6 scenarios database and derives climate change mitigation scenarios envelopes consistent with different interpretations of the Agreement.
- Chapter 4 draws conclusions, as well as potential applications of the criteria framework and Paris-consistent scenario envelopes.

2 Considerations for assessing the consistency of global climate change mitigation scenarios with the Paris Agreement's mitigation objectives

The language in the Paris Agreement's climate mitigation-related objectives does not allow in itself to define a level of global ambition in terms of levels of GHG emissions. Translating these objectives into specific global GHG emissions levels involves a range of considerations (Schleussner et al., 2022[23]), which this chapter discusses. To do so, the chapter first provides context on climate change mitigation scenarios in general as well as on the characteristics of the most recent set of scenarios made available in the scientific literature, namely the AR6 scenarios database, which serves as the basis for the analysis. The chapter then steps through a range of issues and considerations critical to informing an assessment of the consistency of these scenarios with the global objectives in the Paris Agreement.

2.1. Background on global climate change mitigation scenarios

Global climate change mitigation scenarios are an integrated description of possible futures of the human-climate system. They are built using underlying assumptions about future socio-economic trends, including population, GDP, as well as technological development. Based on these assumptions, scenarios project how societal changes may drive the economic system in different directions in terms of primary energy use and supply mix, land use and, as a result, in terms of GHG emissions pathways over time (IPCC, 2022[19]). In doing so, many of them explore least-cost ways of reducing emissions to reach global temperature targets. The most recent of the IPCC scenarios database made available in the context of the publication of the IPCC's AR6 is the basis for the analysis undertaken in this paper (Box 2.1).

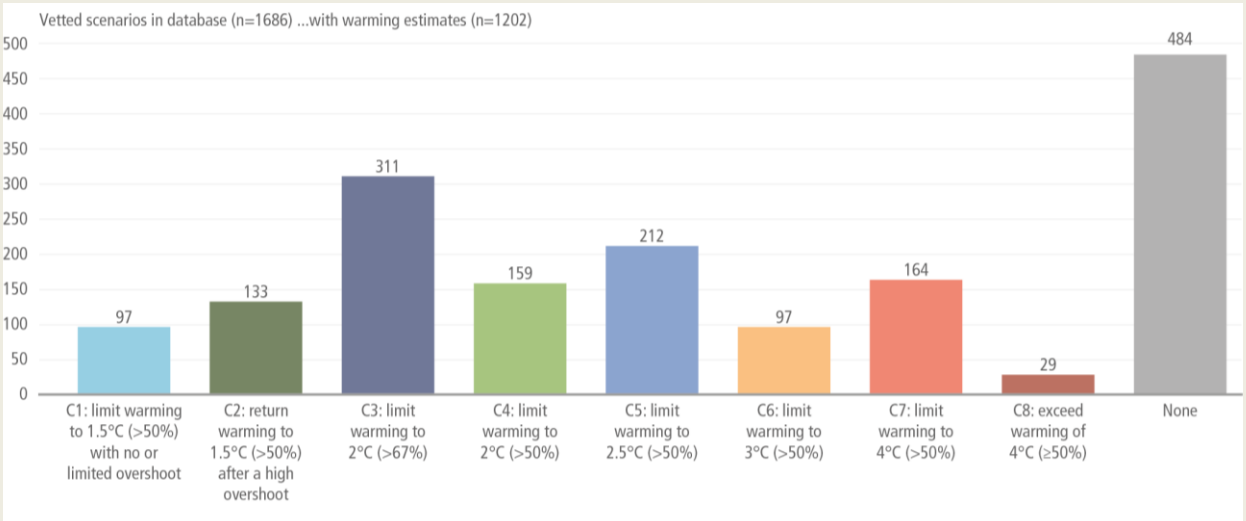
Climate change mitigation scenarios are produced using a range of models. Integrated Assessment Models (IAM) are most commonly used to produce climate change mitigation scenarios. They use a top-down approach to describe the integrated energy-land-economy-climate system and provide "whole system" mitigation trajectories on the long-term. Most IAMs capture all GHG emissions produced across the economy (Riahi et al., 2022[18]). Also commonly used are energy-economy system models. These adopt a hybrid approach, combining top-down macro-economic models and detailed bottom-up energy sector models. An example is the IEA's World Energy Model (WEM), which covers energy supply, transformation and demand to project energy-related CO_2 emissions (IEA, 2021[24]). The IPCC AR6 scenarios database predominantly contains scenarios stemming from IAMs (see Box 2.1).

Box 2.1. The IPCC AR6 Scenarios Database

The IPCC Working Group III on Mitigation of Climate Change, as part of the AR6, collected a large number of quantitative, model-based climate change mitigation scenarios. The AR6 scenarios database builds on previous IPCC assessments, such as those undertaken for the Fifth Assessment Report (AR5) and the Special Report on Global Warming of 1.5°C (SR15). The AR6 collected over 2,200 scenarios with global coverage, of which 700 result in 2°C of median warming or below (Byers et al., 2022[20]). The scenarios gathered in the database were submitted by over 50 different modelling teams and studies (*ibid*). The main providers of scenarios represented in the IPCC AR6 database are global research consortia using IAMs. Every climate scenario included in the AR6 was consistently screened and assessed with respect to its temperature outcomes (IPCC, 2022[19]). Scenarios were then classified based on their likelihood of keeping global temperatures below specific levels (1.5°C, 2°C, 2.5°C, 3°C and 4°C) (Riahi et al., 2022[18]), as summarised in Figure 2.1.

The analysis in this paper relies on all global scenarios from the IPCC AR6 scenarios database that passed the quality screening and provided enough information to receive a climate assessment by the IPCC (around 1,200 scenarios). It is important to note that, as highlighted by the IPCC, such a collection of scenarios is an unstructured scenario ensemble or «ensemble of opportunity», rather than a well-designed statistical sampling of all existing models and scenarios (Riahi et al., 2022[18]). As a consequence, the number of scenarios that are available in a certain temperature category does not say anything about the likelihood of these scenarios or about agreement in the literature (Huppmann et al., 2018[25]).

Figure 2.1. Number of climate change mitigation scenarios by climate category in the IPCC AR6 scenarios database



Note: Many of the collected scenarios did not receive a climate assessment (category "none") because they failed the quality control and vetting processes. The temperature classification shown here relies on the AR6 temperature assessment, which uses a reduced-complexity climate model (MAGICC) to assess the temperature of each scenario instead of relying on the self-assessed temperature outcomes given by individual scenario providers. This allows for a consistent comparison of the temperature outcomes of scenarios across providers.

Source: (Riahi et al., 2022[18]).

Climate change mitigation scenarios provide crucial information on different potential future strategies towards meeting the Paris Agreement's global temperature and emissions objectives. Scenarios can be used to explore specific research questions relevant for a range of policy issues, for example the implications of rapid versus delayed mitigation action. Each scenario lays out a specific mitigation strategy for achieving a given level of mitigation ambition over time (Riahi et al., 2022[18]). For example, some scenarios rely on large amounts of negative emissions to achieve stringent climate mitigation outcomes. Others may place a relative stronger emphasis on demand-side measures (e.g. energy efficiency and energy demand reductions), or on renewables scale-up.

2.2. The Paris Agreement's dual long-term temperature goal

The Paris Agreement calls for "holding the increase in global average temperature to well below 2°C […] and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels". This language is considerably more stringent than that of the preceding global goal in the 2010 Cancun Agreements "to hold the increase in global average temperature below 2°C above pre-industrial levels" (UNFCCC, 2010[26]). The Paris Agreement defines two new temperature benchmarks: "well below 2°C" and a 1.5°C limit. Considering that the scenario literature up until the adoption of the Agreement focused largely on "below 2°C" -consistency, the adoption of the Paris Agreement required a whole new set of global mitigation scenarios to be developed to reflect the increased stringency of the temperature goal. Updated and new scenarios were developed (Rogelj et al., 2018[27]), many of which informed the IPCC 1.5°C Special report and more recently the AR6.

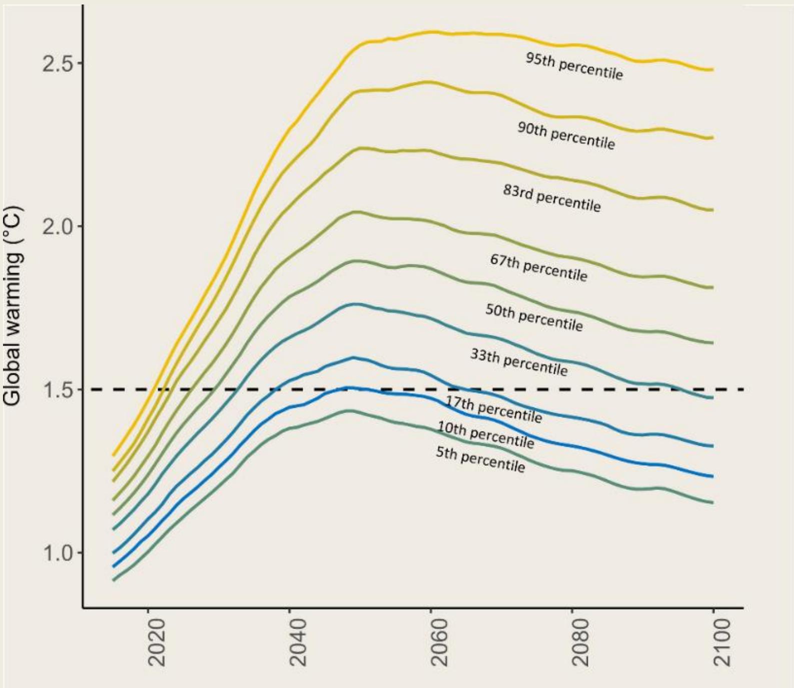
While the language in the Paris Agreement is formulated in terms of two temperature benchmarks, the interpretation of these as two different goals is not necessarily correct. A common practice for scenario developers has been to issue separate scenarios for two distinct temperature targets – 1.5°C scenarios on the one hand, and 2°C, "below 2°C" or "well-below 2°C" scenarios, on the other hand. In practical terms, the decoupling of the two temperatures can create the notion that there is a range of stringencies in the Paris Agreement's temperature goal from which countries and other actors can pick and choose from when setting their targets. This can lead to the undermining of the more stringent end of that target range, thereby undermining of a portion of the carefully negotiated and adopted language of the Agreement. Some interpretations of the Paris Agreement argue that the language in the Agreement defines one unique long-term temperature goal to limit temperature to 1.5°C, allowing or not for a temporary exceedance of that limit to temperatures that are no higher than well below 2°C (Mace, 2016[28]).

The most common way to assess an existing climate change mitigation scenario against a given temperature limit is to calculate the minimum likelihood level at which the scenario maintains global warming below that temperature level (Schleussner et al., 2016[29]). With the Paris Agreement's dual-temperature goal, however, it is important to look at likelihood levels of a scenario simultaneously for both 2°C and 1.5°C temperature limits. The temperature outcomes of scenarios are probabilistic in nature. In this sense, even if scenarios are often tagged as being consistent with one temperature target only, every climate change mitigation scenario has simultaneously a level of likelihood of staying below 2°C as well as another level of likelihood of staying below 1.5°C (Box 2.2).

Box 2.2 Probabilistic temperature outcomes of a mitigation scenario

Estimating the temperature outcome resulting from a climate change mitigation scenario relies most often on inputting the scenario's emissions pathways for different GHGs into a climate model[5]. Another approach is to use so-called carbon budgets, which presents a number of limits and higher degrees of uncertainties, discussed in Box 2.3. A climate model integrates the latest knowledge from physical climate science about the carbon cycle and climate responses to emissions. It assesses the global temperature response to the multi-gas emissions pathways of a scenario, making assumptions about the mitigation of other air pollutants and about the climate equilibrium sensitivity. Assessments of temperature outcomes made by climate models are intrinsically uncertain, and are therefore probabilistic, giving warming projections at different likelihood levels. Figure 2.2 illustrates the probabilistic temperature assessment given by a climate model for a given scenario.

Figure 2.2 Probabilistic temperature assessment of a mitigation scenario



Source: Authors, using data from (Richters et al., 2022[30]).

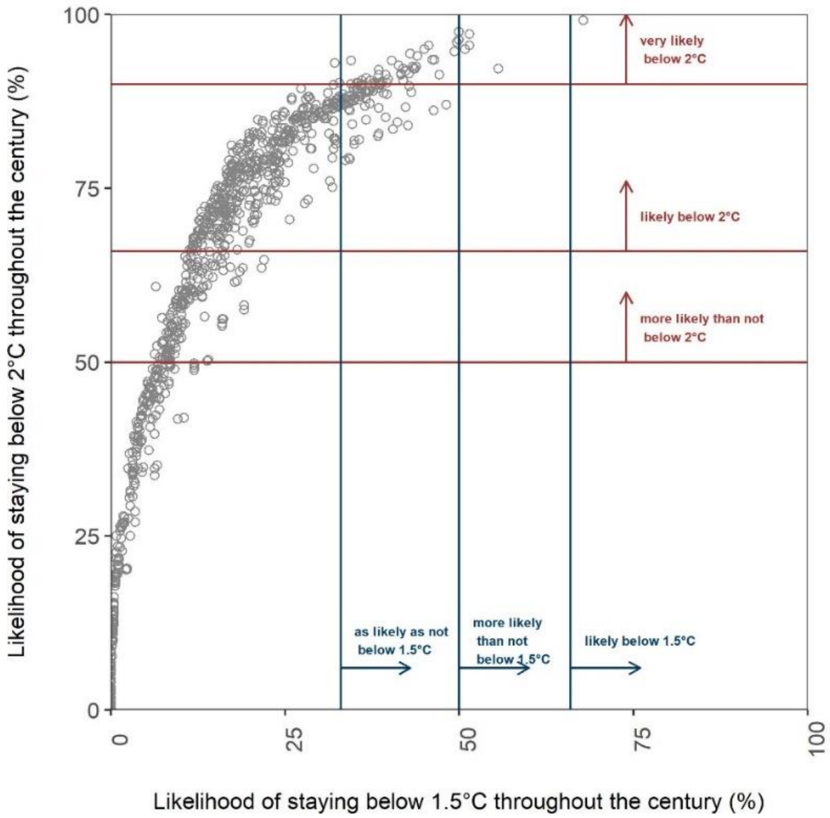
A mitigation scenario is consistent with a given temperature threshold with a given likelihood, or in other words, can lead to different temperature outcomes with different likelihoods. The scenario examined in Figure 2.2 has a 33% chance only to bring back global warming below 1.5°C in 2100, and a 10% chance to keep global warming below 1.5°C throughout the century. In turn, the scenario brings global warming back below 2.5°C in 2100 with a 95% chance. Finding scenarios that are in line with a temperature target means selecting scenarios that stay under that temperature at a certain year or during a period of time, e.g. over the 21st century, with a high enough likelihood.

Source: (IPCC, 2022[19]).

Assessing climate change mitigation scenarios against the Paris Agreement temperature goal requires interpreting the “well-below” and the more stringent “pursuing efforts” formulations in terms of minimum likelihood levels for reaching the 2°C and 1.5°C temperature targets, respectively. Regarding the 2°C threshold, a common practice was to translate the previous “below 2°C” goal formulation as *likely* staying below 2°C (IPCC, 2014[31]), which means having at least a 66% chance of staying below 2°C in the IPCC likelihood scale (IPCC, 2021[32]). The strengthened “well-below 2°C” goal requires higher likelihoods of staying below 2°C of warming. These could be, for example, a *very likely* chance of staying below 2°C of warming (i.e. at least a 90% chance), which corresponds to the next level in the IPCC’s likelihood scale (Schleussner et al., 2022[23]). Regarding the 1.5°C limit, given current emissions levels as a starting point, there exist a few scenarios that “more likely than not “ stay below 1.5°C (50% chance or more), but there are virtually no scenarios available that stay below 1.5°C with a *likely* chance (67% chance or more). The 1.5°C target could, therefore, be translated into mitigation scenarios that keep a reasonable chance of reaching 1.5°C, or, using the IPCC likelihood scale, that are at least *as likely as not* to stay below 1.5°C (33-66% chance, or over).

Figure 2.3 maps all global scenarios with a temperature assessment from the IPCC AR6 database against their respective likelihoods of staying below 1.5°C and below 2°C. It is possible to reflect the Paris Agreement’s formulation of its dual temperature goal, for example by looking at scenarios that have a very likely chance of staying below 2°C *and* that are as likely as not to achieve the 1.5°C target (Schleussner et al., 2016[29]; Schleussner et al., 2022[23]).

Figure 2.3. Likelihoods of keeping warming below 1.5°C and 2°C in IPCC AR6 database scenarios



Note: Each point represents a scenario. All scenarios in the AR6 database that have received a climate assessment by the IPCC (~1200 scenarios) are represented. The axes correspond to the scenarios’ likelihoods of staying below 1.5°C and below 2°C throughout the century, as provided in the AR6 database by the IPCC AR6 climate assessment of the scenarios using the MAGICC climate emulator.
Source: Authors, using the IPCC AR6 scenarios database (Byers et al., 2022[20]).

Box 2.3. Carbon budgets and temperature outcomes

The temperature outcome of certain scenarios can be estimated directly, through the use of climate models, or indirectly, through the use of carbon budgets. In the latter case, to establish scenarios or targets in line with a given temperature outcome, some stakeholders use the remaining carbon budgets provided by the IPCC for different temperature thresholds. A climate change mitigation scenario would be assessed as consistent with a given temperature target if its cumulative emissions remain below the corresponding carbon budget.

A remaining carbon budget indicates the remainder of CO_2 emissions that would be in line with limiting global warming to a specific temperature level. The IPCC estimates the remaining carbon budgets based on the established near-linear relationship between the cumulative CO_2 releases in the atmosphere and the resulting change in global temperature levels, making additional assumptions about non-CO_2 emissions mitigation, and about the warming commitment after cessation of CO_2 emissions – also called Zero Emissions Commitment. The estimates of the remaining carbon budgets provided in the IPCC's latest assessment report are reported for global warming levels of 1.5°C and 2°C in Table 2.1. Several factors limit the precision with which the remaining carbon budgets can be estimated. Therefore, estimates need to specify the likelihood with which warming is maintained within each limit (e.g., limiting warming to 1.5°C with a 67% likelihood).

Table 2.1. Remaining carbon budgets estimated by the IPCC AR6

Global warming since 1850-1900	Remaining carbon budget starting from 2020 (GtCO2)			
	Likelihood level			
	33%	50%	67%	83%
1.5°C	650	500	400	300
2°C	1700	1350	1150	900

Source: (Canadell et al., 2021[33]).

Using a carbon budget approach to assess the temperature implications of climate change mitigation scenarios has significant limitations and this paper does not explore this approach further. By definition, carbon budgets concern CO_2 emissions only; other GHGs, however, have a substantial impact on global warming and on carbon budgets, especially for stringent warming limits. The estimation of carbon budgets for stringent temperature limits made by the IPCC already assumes stringent mitigation of non-CO_2 greenhouse gases; weak non-CO_2 mitigation would otherwise result in carbon budgets close to zero. Even so, the IPCC estimates that its calculated remaining carbon budgets can vary by at least 220 $GtCO_2$ in 1.5°C scenarios, depending on choices related to non-CO_2 emissions mitigation. This means that non-CO_2 emissions are important to consider for reaching 1.5°C targets. Scenarios that model all GHGs may reach the same temperature target yet with very different carbon budgets, because of the different levels of mitigation of non-CO_2 emissions.

Source: (Canadell et al., 2021[33]; Ehlert and Zickfeld, 2017[34]).

2.3. End-of-the-century temperature limits and overshoots

While existing temperature assessments of scenarios tend to focus on scenarios' temperature implications by the end of the twenty-first century, the Paris Agreement does not give a specific time horizon for its long-term temperature goal (UNFCCC, 2015[4]). This has been interpreted in two different ways across the climate science and policy communities. One interpretation is that the inexistence of a time horizon opens the possibility for overshoot scenarios, where the temperature target is exceeded during the course of the century before temperatures are brought back below the target later in the century (Boucher et al., 2016[35]). On the other hand, part of the research and policy community argues that the focus on end-of-century temperatures is not embedded in the Paris Agreement language. This would mean that the temperature target in Article 2.1 applies to peak temperatures over the century as well as to end-of-century temperatures (Mace, 2016[28]; Schleussner et al., 2022[23]).

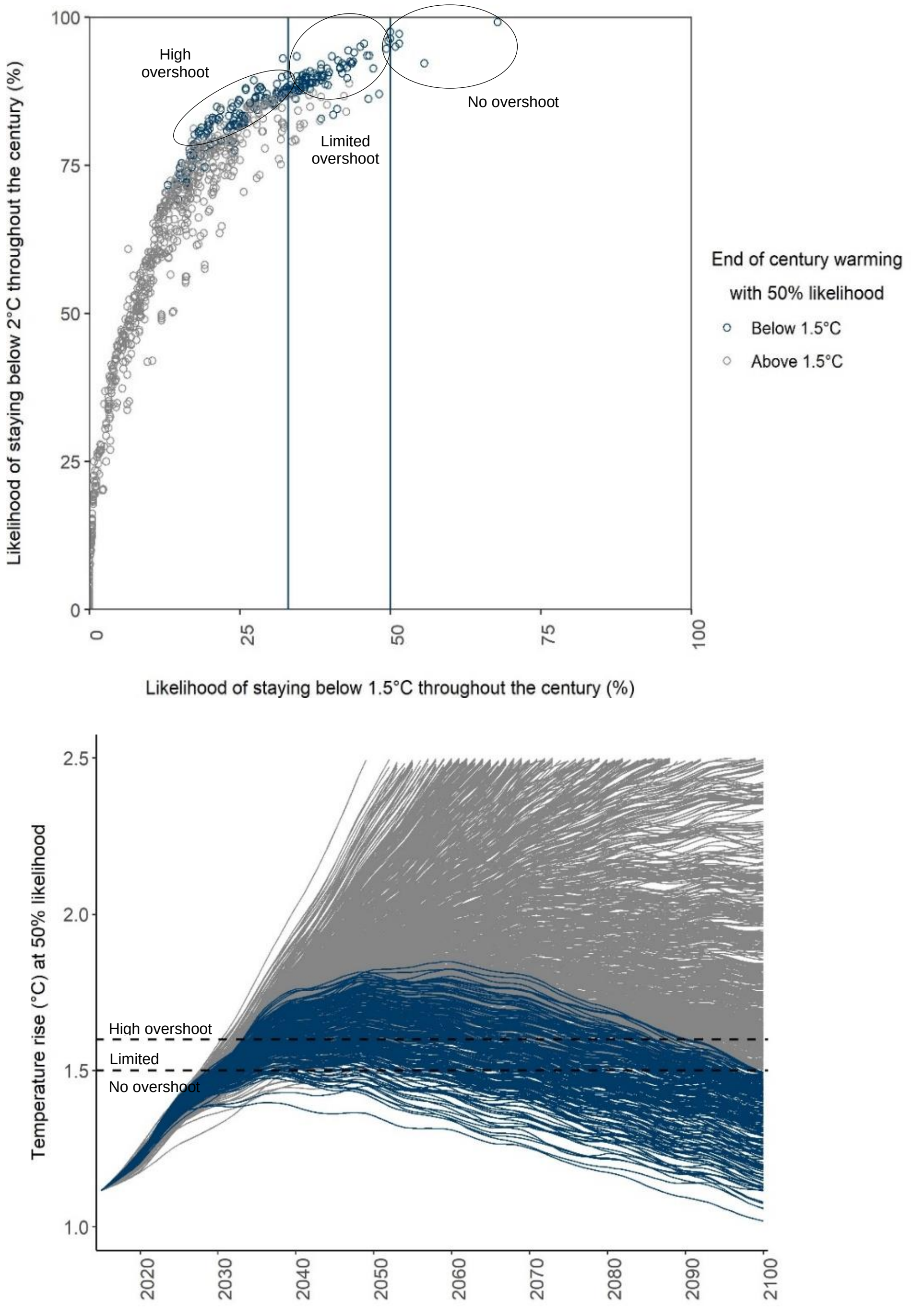
The latest science on climate change makes clear that catch-up climate change mitigation action resulting in overshoots of the 1.5°C temperature target could trigger severe climate change impacts. High and long overshoots of the 1.5°C limit during the century would lead to substantially higher climate impacts and higher risks of crossing climate system tipping points (Drouet et al., 2021[36]; Palter et al., 2018[37]; IPCC, 2018[38]; OECD, 2022[15]; Wunderling et al., 2022[39]; Armstrong McKay et al., 2022[14]). Looking at end of the century temperatures is hence not consistent with the Paris Agreement goal to foster "climate-resilient development (UNFCCC, 2015[4]), nor with the original goal of the 1992 Convention to "prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992[16]). At a minimum, imposing a limit on the amount of overshoot and its duration above the 1.5°C limit can, therefore, be considered a legitimate interpretation of the Paris Agreement. A better understanding of the potential implications of the amount and duration of temperature overshoots remains crucial to the analysis of consistency with the Paris Agreement.

At the level of individual climate change mitigation scenarios, the need to avoid or limit overshoots implies that both end-of-century warming and peak warming over the century need to be considered. **To** select no overshoot scenarios, peak temperatures should be limited to 1.5°C at the same likelihood level as the one considered for end-of-the-century temperatures. If a limited overshoot is allowed, then at that given likelihood level, peak temperatures can exceed the 1.5°C limit to a certain extent.

The present analysis relies on the commonly accepted definitions of the IPCC, whereby a scenario that peaks below 1.6°C (with 50% chance) is considered limited overshoot, and a scenario that peaks at higher temperatures is high overshoot (Rogelj et al., 2018[40]; Riahi et al., 2022[18]). Figure 2.4 shows there are only a limited number of scenarios within the AR6 database that can be considered consistent with keeping temperatures below 1.5°C with a more likely than not chance (i.e. 50% chance or more) by 2100 with limited overshoot during the century. Even fewer options exist for no overshoot of 1.5°C with 50% probability altogether. Scenarios with no or limited overshoot of 1.5°C are also consistent with keeping warming below 2°C over the century with 80% likelihoods or above, as shown by the upper panel of Figure 2.4. None of the high overshoot scenarios are consistent with limiting warming below 2°C with 90% likelihood or more.

With global GHG emissions still increasing every year, the window for a stringent 1.5°C target to stay within reach is narrowing fast. Scenarios that explore such stringent temperature limits require societal, technological and economic changes which are feasible from a modelling perspective. These would, however, constitute unprecedented structural changes in the real world which have raised concerns in terms of their institutional, political and overall feasibility and acceptability (Jewell and Cherp, 2019[41]; Brutschin et al., 2021[42]). The exercise of setting out benchmarks requires careful consideration of the challenges which will accompany a transition.

Figure 2.4. Likelihoods of keeping warming below 1.5°C and 2°C and overshoots of 1.5°C in IPCC AR6 global scenarios



Note: Each point represents a scenario. All scenarios in the AR6 database that have received a climate assessment by the IPCC (~1200 scenarios) are represented. The scenarios' likelihoods of staying below 1.5°C and below 2°C throughout the century (upper panel) and temperature pathways (lower panel) are provided by the IPCC AR6 temperature assessment using the MAGICC climate emulator.
Source: Authors, using the IPCC AR6 scenarios database (Byers et al., 2022[20]).

2.4. Translating the Paris Agreement's emissions objectives

This section discusses how to account for the Paris Agreement's emissions objectives ("reach global peaking of greenhouse gas emissions as soon as possible" and "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century") alongside its long-term temperature goal. To do so, the section explores the relationship between achieving temperature outcomes and net-zero emissions (CO_2 only and GHG), as well as peak and speed of decline of emissions.

While the global temperature goal of the Paris Agreement has received considerable attention in the political and scientific communities since its adoption, the net-zero emissions goal has more recently become widely used by Parties to the UNFCCC as well as the private sector as an operationally actionable target (Geden, 2016[43]; NewClimate Institute, 2022[44]). This stems in part from the fact that a net-zero goal is easily set at the level of an individual country or local entity, whereas translating a global temperature outcome into entity-level emissions requires a range of additional assumptions.

Net zero has become a frame of reference for climate mitigation-related commitments by national, sub-national and private sector entities. As of 2021, net-zero pledges covered a large proportion of the global economy (Black et al., 2021[45]), with many countries and thousands of subnational governments and non-state actors having committed to net-zero targets with different timings and emissions coverages (Hale et al., 2021[46]; Fankhauser et al., 2021[47]). An OECD analysis of 51 net-zero emissions targets adopted by countries reveals that a majority of net-zero targets cover all GHG emissions, and that most countries aim to achieve net-zero by 2050 (Jeudy-Hugo, Lo Re and Falduto, 2021[48]). Another survey of over 4,000 entities (countries, sub-national governments, cities and companies) finds that net-zero pledges are split equally between those covering all GHGs and those covering CO_2 only (Black et al., 2021[45]).

Reaching global net-zero CO_2 emissions is necessary to, in the best estimate, stabilise warming to any level (IPCC, 2018[38]; Arias et al., 2021[49]), because of the linear relationship between cumulative anthropogenic CO_2 emissions and global warming. As illustrated in the upper panel (filled circles) of Figure 2.5, most scenarios in the AR6 database reach net-zero CO_2 before the end of the century, regardless of whether temperatures are kept at levels in line with the Paris Agreement temperature goal. There exist in effect a very large number of scenarios which achieve net-zero CO_2 by 2100 but do not keep warming below 1.5°C nor even below 2°C by the end of the century (Figure 2.5).

While reaching net-zero CO_2 emissions is required to *stabilise* global temperatures, reaching and sustaining net-zero GHG emissions is likely to ensure a gradual *decline* in global temperatures[6] (IPCC, 2021[32]), taking into account uncertainties about the long-term response of global temperatures to the cessation of emissions. Temperatures can be stabilised at 2°C or 1.5°C without requiring GHG emissions to reach and be maintained at net zero (Tanaka and O'Neill, 2018[50]), as shown by many scenarios in the IPCC AR6 database (Byers et al., 2022[20]), and as illustrated in Figure 2.5 (lower panel, empty blue circles). Indeed, around half of the scenarios limiting warming to 1.5°C with no or limited overshoot and another half of scenarios limiting warming to 2°C with a likely probability do not reach net-zero GHG emissions before 2100 (Riahi et al., 2022[18]). This is because it is sufficient to only gradually reduce emissions of GHG with a short lifetime in the atmosphere to stabilise their global temperature contribution (Forster et al., 2021[51]). Reaching net-zero GHG emissions[7] in addition to net-zero CO_2 emissions is, however, required by the Paris Agreement Article 4.1 as it would likely result in declining temperatures after an initial peak. Bending the temperature curve with global net-zero GHG emissions is necessary to

[6] For this statement to be true, GHG emissions have to be aggregated using global warming potentials over 100 year (GWP_{100}), as agreed under the Paris rulebook.

[7] aggregated using global warming potentials over 100 year (GWP_{100}), as agreed under the Paris rulebook. See Glossary.

avoid dangerous levels of climate change in the long-term; stabilizing global warming only would mean committing to long-term climate risks – for example long-term sea-level rise (Mengel et al., 2018[52]).

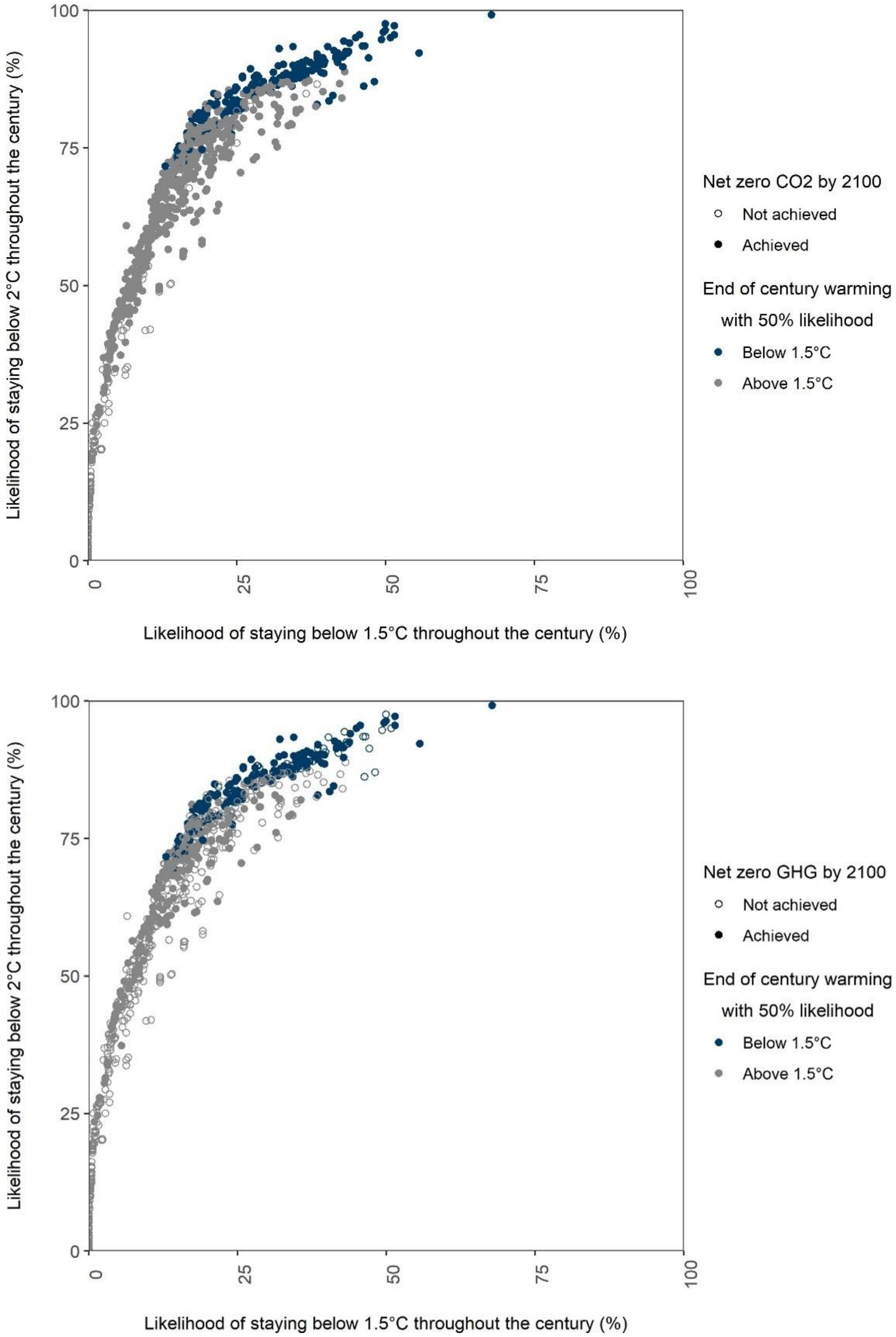
Accounting for non-CO_2 GHG emissions is not only essential for achieving declining temperatures in the long term, but also for limiting peak warming. Peak warming in mitigation scenarios is indeed determined by both the cumulative net-CO_2 emissions until the time of net-zero CO_2, and by the warming contribution of other GHGs (Riahi et al., 2022[18]). Rapid reductions in non-CO_2 GHGs, particularly methane, would allow to lower the level of peak warming (*ibid*). If non-CO_2 emissions do not decline, the remaining carbon budget to reach stringent temperature limits would actually be reduced to zero (see Box 2.2).

The relationship between the timings of net-zero GHG and CO_2 emissions and temperature outcomes is however complex. In fact, the relationship between the timing of net-zero CO_2 or net-zero GHG and the median peak temperature is far from linear (Riahi et al., 2022[18]). Figure 2.6 shows that across all scenarios collected by the IPCC, there is only a loose relationship between the year of net-zero CO_2 emissions (top left panel) or the year of net-zero GHG emissions (top right panel) and median peak warming (or equivalently the amount of overshoot of 1.5°C) over the century. Scenarios that reach net-zero CO_2 before 2050, for example, have variable levels of overshoots of the 1.5°C target, reaching up to 1.76°C of median peak temperature, which corresponds to a high overshoot (IPCC, 2022[19]). Conversely, several scenarios achieve limited overshoots of 1.5°C while reaching global net-zero CO_2 and net-zero GHG emissions late in the second half of the century.

Instead of a precise timing for net-zero CO_2 and GHG, what determines the magnitude of peak global warming is the amount of emissions accumulated until the point of net zero (Riahi et al., 2022[18]), i.e. the shape of the CO_2 and GHG emissions pathways until net-zero (Rogelj et al., 2019[13]) and in particular the speed of near-term (i.e. by 2030) reductions in emissions. The years of 50% CO_2 and GHG emissions reductions compared with 2019 levels, for example, are far more correlated with the level of peak warming than the years of net-zero CO_2 and GHG emissions, as illustrated by the bottom panels in Figure 2.6. This means that early and deep emissions reductions in the near term determine the level of peak warming, whereas the timing of net-zero CO_2 emissions determines the timing of peak warming (Rogelj et al., 2019[13]). As a consequence, selecting climate change mitigation scenarios based on the year of net-zero emissions (e.g. 2050) overlooks the amount of emissions accumulated before the date of net zero, and consequently the level of peak temperature.

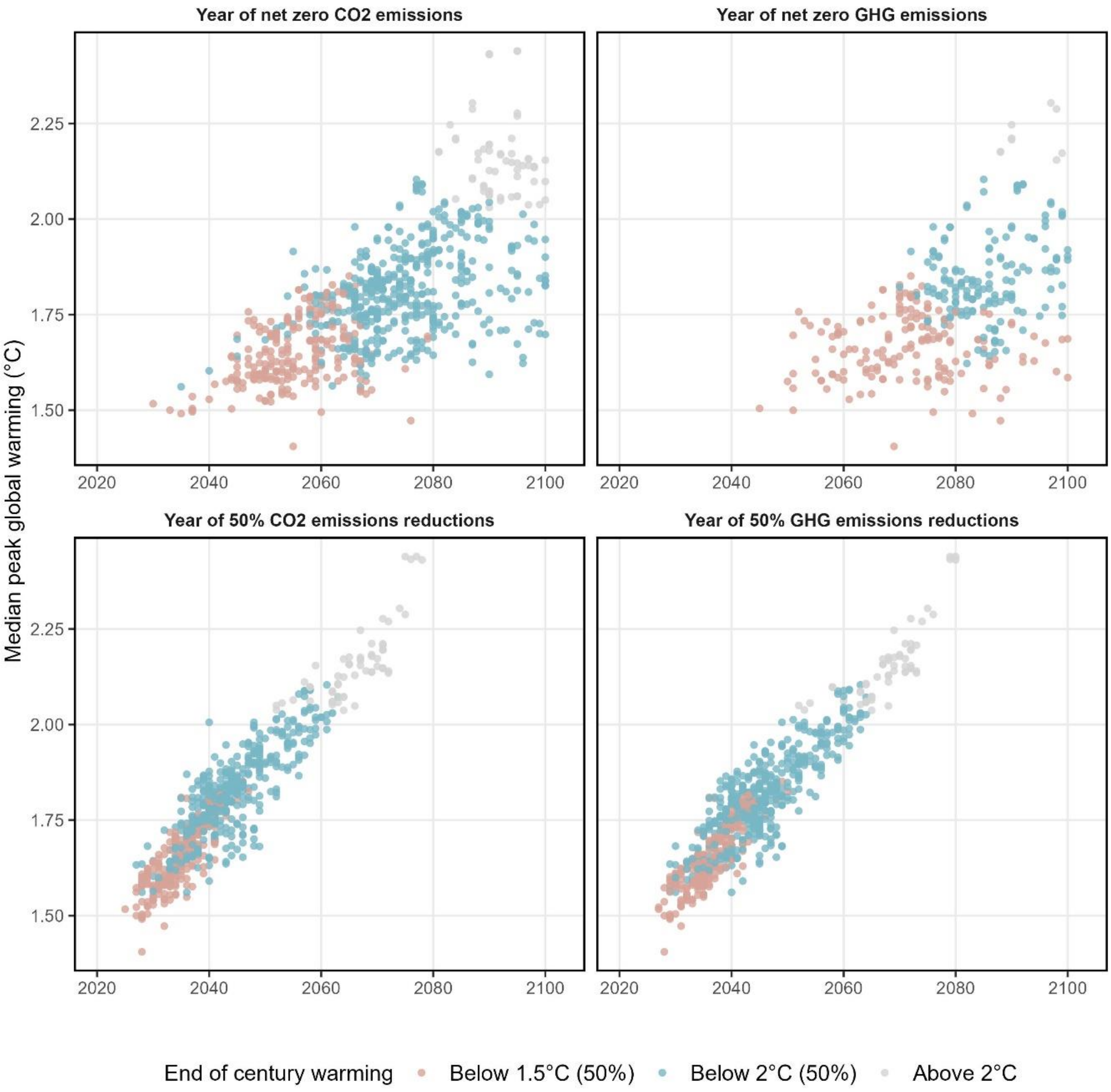
In selecting Paris Agreement consistent scenarios, it is, therefore, crucial to reflect all elements of the Paris Agreement temperature and emissions objectives and to consider complete GHG pathways to net zero and beyond, as argued by a range of climate science research (Rogelj et al., 2019[13]; Schleussner et al., 2022[23]; Brecha et al., 2022[53]). To reflect the different mitigation-related objectives of the Paris Agreement, emissions pathways would need to make GHG emissions peak "as soon as possible", and reach net-zero GHG emissions "during the second half of the century", in addition to maintaining global warming below the Paris Agreement's Article 2.1 temperature thresholds (Schleussner et al., 2022[23]).

Figure 2.5. Temperature outcomes and net-zero CO_2 and GHG emissions in IPCC AR6 global scenarios



Note: Each point represents a scenario. All scenarios in the AR6 database that have received a climate assessment by the IPCC (~1200 scenarios) are represented. The scenarios' likelihoods of staying below 1.5°C and below 2°C throughout the century and at the end of the century are provided by the IPCC AR6 climate assessment of the scenarios in the database, using the climate emulator MAGICC.
Source: Authors, using the IPCC AR6 scenarios database (Byers et al., 2022[20]).

Figure 2.6. Relationship between median peak warming and years of net-zero CO_2 and GHG emissions (top), versus years of 50% CO_2 and GHG emissions reductions (bottom) in IPCC AR6 global scenarios



Note: Each point represents a scenario. 50% emissions reductions are calculated in comparison with 2019 emissions levels. All scenarios in the AR6 database that have received a climate assessment by the IPCC (~1200 scenarios) are represented, except scenarios that never reach net-zero CO_2 (respectively GHG) emissions during the century in the top panels, and 50% CO_2 (respectively GHG) emissions reductions compared to 2019 levels in the bottom panels. The scenarios' median peak warming, years of net zero and years of 50% emissions reductions are provided by the IPCC AR6 climate assessment using the MAGICC7 climate emulator and harmonized and infilled emissions.
Source: Authors, using the IPCC AR6 scenarios database (Byers et al., 2022[20]).

2.5. Implications of uncertainties in climate responses to greenhouse gas emissions

The consideration of uncertainties in the scale of response of the climate to GHG emissions is key to the question of the consistency of mitigation scenarios with the global Paris Agreement objectives. While there is today a high degree of confidence in the fundamental science on climate change and the severity of associated impacts, there exist different types of uncertainties in how climate change will actually unfold. While not the focus of this paper, these scientific uncertainties have to be kept in mind when assessing the consistency of individual climate change mitigation scenarios with the Paris Agreement, as they provide information on climate risks and support the need for a risk management approach.

Temperature outcomes of mitigation scenarios are assessed using metrics of climate sensitivity[8] that estimate the temperature response to GHG concentration in the atmosphere (OECD, 2021[54]). These metrics translate complex responses within the Earth system, and their "true" value is unknown. Scientists work with central values of estimated ranges, but uncertainties around these metrics translate directly into uncertainties for global mitigation scenarios that would ensure that global warming is maintained below 1.5°C or 2°C. Uncertainties are in part captured by climate models' distributions of temperature responses to emissions. Of concern, however, the equilibrium climate sensitivity is "fat-tailed" (Ackerman, Stanton and Bueno, 2010[55]; Wagner and Weitzman, 2018[56]; Arias et al., 2021[49]), which means that it is hard to rule out values of equilibrium response which are significantly greater that the most likely estimate.

There exist also uncertainties in the speed at which climate change and its impacts will unfold under different warming levels. Scientific advances over the past decade reveal that the occurrence of many types of physical hazards may have become more likely under lower warming levels than previously thought. Notably, while two decades ago climate system tipping points were projected to be crossed under high levels of warming, there are today concrete signs that we are approaching tipping points considerably sooner than timelines projected in earlier modelling. In fact, some climate tipping points may already be crossed at global warming levels between 1.5 and 2°C, some of them even below 1.5°C (Armstrong McKay et al., 2022[14]; OECD, 2022[15]). This shows, for example, that whether temperatures are kept under 1.5°C during the 21st century or whether temperatures are brought back to 1.5°C by 2100 after a high overshoot can lead to considerably different climate change futures.

Recent scientific advances and the existence of these scientific uncertainties support the need for a precautionary approach in developing climate change mitigation benchmarks to inform strategies to be taken by countries, businesses and other actors. Since the adoption of the Paris Agreement, the evolution of the scientific understanding of climate change increasingly implies that limiting temperature rise to 1.5°C is no longer an aspiration, but a necessity to prevent catastrophic and permanent impacts. Identifying mitigation scenarios that are in line with the Paris Agreement requires interpretating its objectives, with more stringent or lenient interpretations being possible but within clear bounds.

Assessments of Paris-consistency will need to keep evolving hand in hand with advances in our understanding of the climate response to anthropogenic GHG emissions. Scenarios that may have been considered as Paris-aligned when the Agreement was adopted in 2015, today, and in the future, are unlikely to remain the same. This is due to the improved understanding of the implications of different levels of temperature increase for climate change outcomes and overall resilience. In addition, scenarios can rapidly become outdated as they diverge from real world emissions pathways.

[8] These include the equilibrium climate sensitivity (ECS) and the transient climate response (TCR), two key metrics for understanding present and future human-made climate change. The ECS refers to the long-term change in global mean temperature following a doubling of atmospheric CO_2-equivalent concentration and after the climate has reached equilibrium again. The TCR is a shorter-term metric for the amount of warming that occurs at the time the CO_2-equivalent concentration doubles following a linear and steady increase in emissions (OECD, 2021[54]).

3 Possible reference envelopes of global scenarios consistent with the Paris Agreement

3.1. Possible criteria for Paris-consistency

Building on the issues and considerations detailed in Chapter 2, this section suggests possible criteria for selecting climate change mitigation scenarios and emissions pathway envelopes consistent with the Paris Agreement temperature and emissions objectives. These criteria are identified as a way forward for translating the Paris Agreement mitigation objectives into formulations of temperature and emissions outcomes in scenarios, building on existing criteria proposed in the scientific literature (Schleussner et al., 2022[23]; Brecha et al., 2022[53]).

Table 3.1 sets out two possible sets of criteria for selecting global scenarios in line with the Paris Agreement mitigation-related provisions, corresponding to two different levels of stringency in the interpretation of these objectives. The first set of criteria proposes a more stringent interpretation of the Paris Agreement's temperature and emissions objectives, in accordance with the discussion in Chapter 2and so as to reflect the ultimate goal of the UNFCCC of avoiding the most dangerous impacts of climate change. The less stringent interpretation loosens some of the criteria and may be considered less closely aligned with the Agreement, while nevertheless providing a useful point of comparison. This paper recognises that a variety of other options for criteria could be considered as broadly in line with the Paris Agreement's long-term objectives. As discussed in Chapter 2and section 2.5 in particular, more lenient interpretations of the Agreement would, however, ignore the overwhelming evidence and knowledge on climate change and the latest developments in climate politics, potentially diverting focus from economically, financially and technologically feasible options for climate change mitigation.

Criteria 1 and 2 translate the Paris Agreement's goal of "pursuing efforts to limit the temperature increase to 1.5 °C". **Criterion 1**, for both stringency options, specifies that the 1.5°C target is to be met by the end of the century with a more likely than not chance of at least 50%, as discussed in section 2.2. Aside from this end-of-the-century temperature target, this paper argues that mitigation scenarios consistent with Article 2 and with fostering climate-resilient development also need to limit the chance of overshooting the 1.5°C temperature target throughout the century, as argued in section 2.3. This is ensured by **criterion 2** which imposes a limit in the magnitude of overshoots above 1.5°C. The magnitude of overshoot can be measured as the amount by which the peak temperature in the century exceeds 1.5°C at the 50% likelihood level. In both criteria sets, the criterion requires peak temperatures not to exceed 1.6°C throughout the century, with a more likely than not or 50% chance. Equivalently, a maximum overshoot of 0.1°C above 1.5°C at the 50% likelihood level is allowed. Such a level of overshoot is considered as limited overshoot in IPCC assessments (Riahi et al., 2022[18]).

Table 3.1. Criteria for selecting global scenarios consistent with the Paris Agreement's mitigation-related objectives

<table>
<tr><th rowspan="2">Paris Agreement Article</th><th rowspan="2">Paris Agreement mitigation goal and objectives</th><th colspan="2">Criteria</th></tr>
<tr><th>More stringent interpretation</th><th>Less stringent interpretation</th></tr>
<tr><td>2.1a</td><td>"pursuing efforts to limit the temperature increase to 1.5°C"</td><td colspan="2">Criterion 1
1.5°C in 2100
In 2100, the scenario must hold global warming below 1.5°C with at least <u>50%</u> chance.

Criterion 2
no or limited overshoot of 1.5°C
Throughout the century, the scenario must hold global warming below <u>1.6°C</u> with 50% chance.</td></tr>
<tr><td>2.1a</td><td>"holding the increase in global average temperature to well below 2°C"</td><td>Criterion 3
well below 2°C throughout the century
Throughout the century, the scenario must hold global warming below 2 °C with at least <u>90%</u> chance.</td><td>Criterion 3
well below 2°C throughout the century
Throughout the century, the scenario must hold global warming below 2 °C with at least <u>78.3%</u> chance.</td></tr>
<tr><td>4.1</td><td>"aim to reach global peaking of greenhouse gas emissions as soon as possible [...and] achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century"</td><td>Criterion 4
peak GHG emissions
The scenario must ensure that global GHG emissions peak at or before <u>2025</u>.

Criterion 5
net-zero GHG emissions
The scenario must achieve global <u>net-zero GHG</u> emissions before 2100.</td><td>Criterion 4
peak GHG emissions
The scenario must ensure that global GHG emissions peak at or before <u>2030</u>.

Criterion 5
near net-zero GHG emissions
The scenario must achieve global <u>net-zero CO_2</u> emissions before 2100, with <u>residual net GHG emissions of 5 Gt or less</u> in 2100.</td></tr>
<tr><td colspan="2">Number of scenarios in the IPCC AR6 database</td><td>26</td><td>55</td></tr>
</table>

Note : Global warming is defined as the increase in global mean surface temperature (GMST), relative to the reference period 1850-1900. See Glossary for a full definition of the use of this term in this paper. See Glossary for a definition of the likelihood of staying below a given temperature.
GHG emissions are calculated using Global Warming Potentials over 100 years (GWP_{100}). See Glossary for full definitions of the concepts of GHG emissions, net zero GHG and net zero CO_2 as used in this paper.
Source: Authors, building on (Schleussner et al., 2022[23]; Brecha et al., 2022[53]).

Criterion 3 specifies the likelihood threshold for the "well below 2°C" objective. As discussed in section 2.2, because the previous "below 2°C" goal from the 2010 Cancun Agreements was usually translated as likely staying below 2°C (i.e. 67% chance), the strengthened "well below 2°C" from the 2015 Paris Agreement is here translated using higher likelihood levels of staying below 2°C, i.e. a very likely chance (90% chance) for the more stringent criterion. The less stringent interpretation loosens this criterion to a lower 78.3% chance, a likelihood level in the middle between very likely (90%) and likely (67%) in the IPCC scale. Since, as discussed in Section 2.3, an end-of-century horizon for the well below 2°C target is not embedded in the Paris Agreement language, this criterion requires these likelihoods never to be exceeded throughout the century. Criterion 2 essentially guarantees both that the 2°C temperature limit is very likely never reached over the full course of the century, and, as a corollary, that the median maximum temperature reached is well below 2°C.

Criteria 4 translates the emissions objective in Article 4.1 of aiming "to reach global peaking of greenhouse gas emissions as soon as possible", in accordance with section 2.4. As discussed in this section, reducing the amount of emissions produced before net zero thanks to fast emissions reductions already this decade is critical for ensuring that peak warming is limited and that the most dangerous impacts of climate change are avoided. Accordingly, **Criterion 4** proposes that global GHG emissions peak either at or before 2025 in its more stringent option, and at or before 2030 in its less stringent one.

Criterion 5 additionally translates Article 4.1's objective of achieving "a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century", which is likely to ensure a gradual decline in global temperatures in the long term. The less stringent interpretation loosens this criterion by requiring net-zero CO_2 emissions and very strong reductions in total GHG emissions to reach near net-zero GHG emissions, but still allowing for marginal residual net GHG emissions of 5 Gt or less by 2100. While allowing for these residual net emissions is not fully in line with the language in the Paris Agreement, it provides a symmetric approach to relaxing the stringency applied to other criteria. Considering that the year of net-zero GHG emissions correlates weakly with median peak warming (Figure 2.6), this paper opts to consider these marginal net emissions of GHGs in the set of criteria. Relaxing Criterion 5 notably allows to capture a number of scenarios that do not reach strictly net-zero GHG emissions because of modelling constraints and design choices. These scenarios are yet still useful to consider, especially in the medium term, as they do both reach net-zero CO_2 and achieve very strong GHG emissions reductions, resulting in the achievement of stringent temperature goals with limited peak warming. The 5Gt threshold for residual net GHG emissions at the end of the century could be further discussed and revised in future work and in future uses of the criteria framework. Criterion 5 does not impose an exact year by which net-zero CO_2 or GHG must be achieved, because of the flexible relationship between the timings of net-zero emissions and the temperature outcomes of emissions pathways, illustrated in section 2.4.

3.2. Resulting scenario envelopes

This section derives two reference envelopes of global scenarios respectively consistent with the two sets of criteria from Table 3.1, corresponding to two levels of stringency in the interpretation of the Paris Agreement temperature and emissions objectives. Table 3.2 lists the specific variables used in this paper to select reference envelopes matching the criteria described above. To allow the assessment of scenarios against these criteria, scenarios report certain data, including aggregated GHG emissions and CO_2 pathways, as well as a probabilistic temperature assessment of their emissions pathways. Overall, around 1,200 scenarios from the IPCC AR6 scenarios database are assessed against the consistency criteria (see Box 2.1).

Table 3.2. Scenario data used for the proposed criteria-based assessment

Criteria	Scenario data used
Criterion 1	Likelihood of staying below 1.5°C in 2100
Criterion 2	Peak global warming over the century at the 50% likelihood level.
Criterion 3	Likelihood of staying below 2°C during the century
Criterion 4	Year of peak GHG emissions
Criterion 5	Year of global net-zero GHG emissions Year of global net-zero CO_2 emissions Net GHG emissions in 2100

Note: Criterion 1 can also be assessed using scenarios' 2100 temperatures at the 50% likelihood level. Criterion 1 then translates as "the scenario must result in 1.5°C or less in 2100 at the 50% likelihood level". This paper's selection of envelopes relies on AR6 temperature assessments. In particular, the AR6 provides interpolated emissions values for each emissions pathway to increase their temporal granularity. This paper's selection of scenarios uses the interpolated values to find the exact years of net-zero emissions.
Source: Authors.

Applying the more or less stringent criteria set to filter the scenarios gathered in the IPCC AR6 scenarios database yields two envelopes of 26 (stringent interpretation) and 55 (less stringent interpretation) mitigation scenarios. This represents less than 4% and 8%, respectively, of all scenarios that remain below 2°C with 50% likelihood (categories C1 to C4 in the IPCC classification[9]) in the AR6 database. The list of scenarios in each envelope and the associated emissions data (5-yearly GHG and CO_2 emissions for all selected scenarios) are provided in 4.3.Annex A. Both Paris-consistent envelopes are subsets of the IPCC C1 category of scenarios ("1.5°C with no or limited overshoot", 97 scenarios – see box 2.1), as they add further stringency with additional criteria on the likelihood of staying below 2°C and on reaching net-zero GHG emissions.

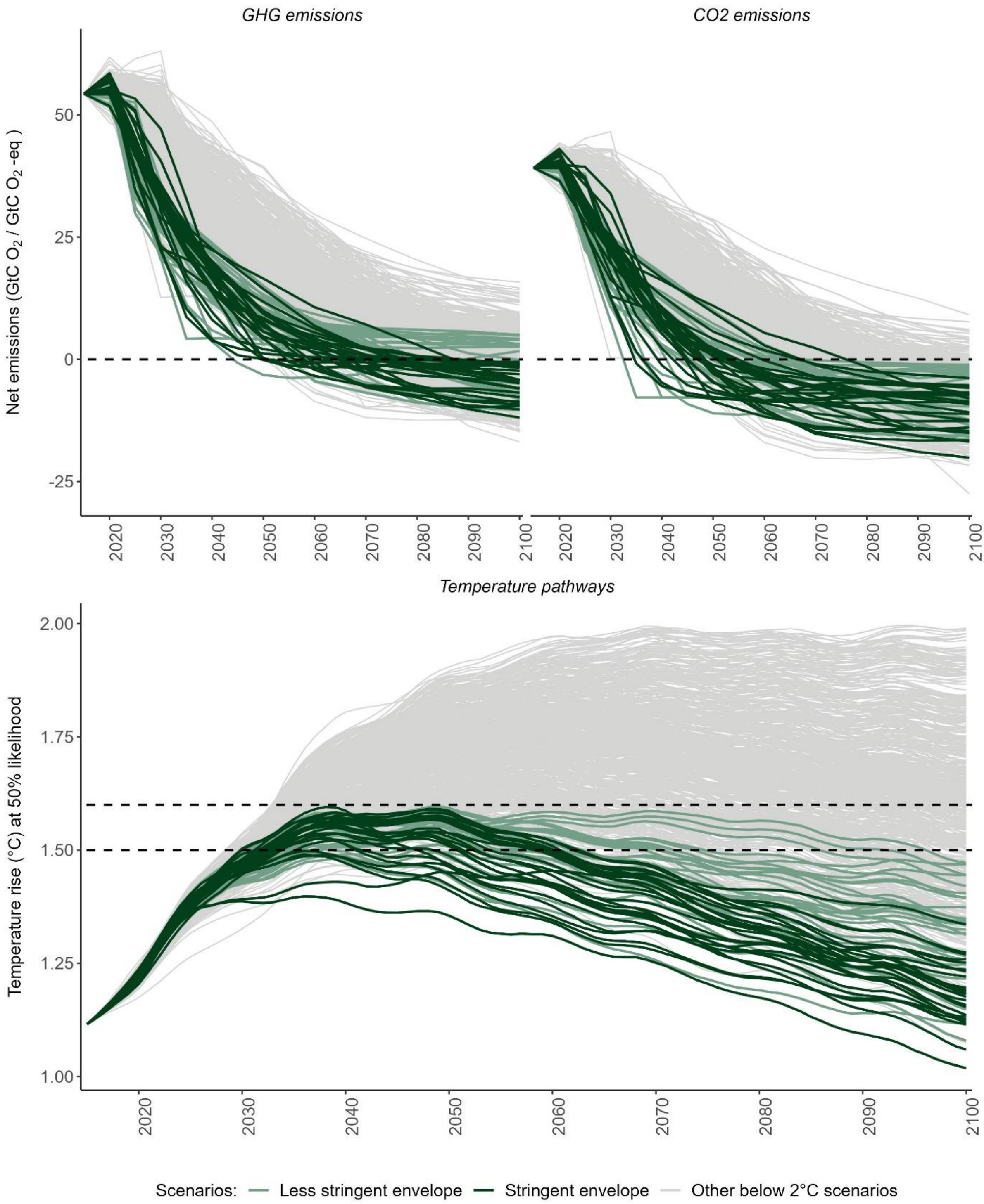
Figure 3.1 further illustrates that only a very small subset of likely below 2°C scenarios in the AR6 database are in line with the Paris Agreement, according to the latest science and to the proposed interpretations of the Agreement's objectives. Figure 3.1 plots the selected Paris-consistent emissions and temperature pathways, as well as likely below 2°C pathways in the database that failed to meet one of the two sets of Paris-consistency criteria. No scenario likely resulting in 2°C or below by the end of the century, and only a fraction of the scenarios that return to 1.5°C by the end of century with 50% likelihood, are selected.

The selection results demonstrate that a thorough science-based approach taking into account all mitigation-related objectives embedded in the Agreement is necessary to define and select Paris-consistent global mitigation scenarios. Other interpretations and selections than those put forward here are possible. However, commonly seen loose and less holistic approaches considering only portions of the mitigation objectives (e.g. "net zero by 2050", "1.5°C in 2100", or "well-below 2°C" only) do not allow to define reference climate change mitigation scenarios that aim to avoid the dangerous levels of climate change the Paris Agreement mitigation objectives were created to avoid.

In fact, it is key for all part parts of the mitigation objectives in the Paris Agreement to be taken into account together and to apply all criteria in a combined manner. For example, selecting scenarios returning to 1.5°C by the end of the century with 50% chance, which are usually branded as "1.5°C scenarios", results in an envelope of 230 scenarios. There are also over 300 "net-zero GHG by 2100" and over 60 "net-zero CO_2 by 2050" scenarios, several of which do not keep global warming below 1.5°C with 50% likelihood. This again proves that such criteria alone are not adequate for selecting Paris-consistent scenarios. These examples demonstrate that a comprehensive science-based criteria framework such as the one proposed in this paper is required for defining the Paris-consistency of scenarios. 4.3.Annex B further illustrates these results by showing the relative size of scenarios sets when applying the criteria alone or in combination.

[9] See the overview of IPCC scenarios classification in section 0 and Figure 2.1.

Figure 3.1. Reference envelopes of scenarios satisfying proposed Paris-consistency criteria



Note: Pathways in green correspond to scenarios that fulfil Criteria 1, 2, 3, 4 and 5. Pathways in dark green satisfy the more stringent interpretation for each of the criteria, while pathways in light green satisfy the less stringent level of interpretation of the criteria, but not the stringent level. The other pathways (in grey) correspond to all other scenarios that remain below 2°C with a likely (66%) chance or more throughout the century.
Source: Authors, using data from the IPCC AR6 scenarios database (Byers et al., 2022[20]).

4 Implications and potential applications

This Chapter explores applications of the criteria framework and of the scenario envelopes for Paris ambition benchmarking. The analysis and criteria framework have direct implications for net-zero target setting practices (Section 4.1), and for ambition monitoring and alignment measurement against the Paris Agreement (Section 4.2). Potential uses of the Paris-consistent envelopes for informing net-zero transition policies are also explored (Section 4.3).

4.1. The criteria framework and scenario envelopes can help improve current net-zero target setting practices

Global climate change mitigation scenarios such as those explored in this paper already play a key role for formulating net-zero or decarbonisation targets consistent with the ambition of the Paris Agreement. Such scenarios are used to inform emissions targets setting by governments, sub-national governments, corporates and investors (van Beek et al., 2020[57]), for example by supporting science-based targets for corporates (Krabbe et al., 2015[58]).

The Paris-consistent scenario envelopes derived in Chapter 3can help inform how to set net-zero targets consistent with the mitigation ambition of the Paris Agreement and with the latest climate science. The analysis in Chapter 2 shows that both net-zero CO_2 and net-zero GHG emissions need to be reached this century to achieve the Paris objectives. Furthermore, the analysis demonstrates that beyond the timing of net zero, it is the speed of emissions reductions in reaching net zero that will actually determine the level of peak global warming and whether the Paris Agreement temperature objective can be met (Section 2.4 and Figure 2.6). In particular, the shape of emissions pathway in the near-term (before 2030) will determine the level of peak warming during the century. Looking at ranges of emissions reductions benchmarks and milestones derived from the Paris-consistent scenario envelopes from Chapter 3Table 4.1 additionnally makes clear that beyond CO_2, emissions, reductions across all Kyoto greenhouse gases are crucial to achieve the Paris Agreement temperature goal. The ranges of reduction levels for the different gases in the scenario envelope are also determined by the fact that less ambition on CO_2 emissions reductions in some scenario is counterbalanced to some extent by more ambitious reductions of emissions from other gases and reversely.

Table 4.1. Global emissions benchmarks and milestones consistent with stringent and less stringent interpretations of Paris ambition

(dark green)	Stringent Paris-consistent envelope
(light green)	Less stringent Paris-consistent envelope

Benchmarks: emissions reductions relative to 2019			
	2030	2040	2050
Total GHG	29% – 59%	61% – 91%	76% – 100%
	35% – 60%	60% – 92%	74% – 100%
Carbon dioxide (CO_2)	29% – 68%	63% – 110%	79% – 120%
	37% – 70%	60% – 114%	76% – 120%
Methane (CH_4)	22% – 56%	40% – 65%	45% – 71%
	21% – 59%	35% – 64%	40% – 70%
Nitrous dioxide (N_20)	0% – 41%	2% – 49%	-2% – 59%
	1% – 36%	2% – 48%	-2% – 60%
Milestones: year of 50% emissions reductions compared to 2019 levels			
Total GHG	2029 – 2036		
	2028 – 2036		
Carbon dioxide (CO_2)	2028 – 2036		
	2028 – 2036		
Milestones: year of net-zero emissions			
Total GHG	2051 – 2088		
	2051 -		
Carbon dioxide (CO_2)	2038 – 2067		
	2037 – 2067		

Note: Numbers in the table correspond to 5th-95th percentile values in the more stringent Paris-consistent scenarios envelope (dark green) and in the less stringent Paris-consistent scenarios envelope (light green), respectively, derived in Chapter 3
Source: Authors, using data from the AR6 scenarios database (Byers et al., 2022[20]).

These considerations allow to identify good practices to improve and strengthen net-zero and decarbonisation targets for all stakeholders. It is important to note that the scale and pace of decarbonisation will be different across countries and sectors, and targets set by individual actors will differ from global benchmarks and milestones such as those given in Table 4.1. The geographical downscaling of global pathways is challenging because it requires to account for equity considerations, which are not considered in this paper. The analysis on global-level benchmarks and analysis in this paper show nonetheless that the following practices could help improve net-zero targets set by all types of actors.

- **Reduction targets need to be set for individual Kyoto gases in addition to targets for CO_2 and aggregated GHG emissions**. Paris-consistent scenarios such as those selected in this paper and the broader climate science research show that deep reductions in emissions from all gases are necessary, beyond CO_2. Methane (CH_4) emissions, in particular, contribute strongly to short-term global warming and constitute an important share of GHG emissions. However, methane is rarely covered by national and corporate targets. As shown by Table 4.1, methane emissions need to be reduced at rates comparable to those for CO_2 emissions. The role of non-CO_2 mitigation and the need for specific targets for individual gases beyond CO_2 is also largely supported by the scientific literature (Ou et al., 2021[59]; Cain et al., 2021[60]; Nisbet et al., 2021[61]; Pekkarinen, 2020[62]; Nisbet et al., 2020[63]; Allen et al., 2022[64]).

- **Targets need to be set for reaching both net-zero CO_2 emissions and net-zero GHG emissions.** Many existing net-zero targets only cover CO_2 emissions, or do not specify whether they cover CO_2 or GHG (NewClimate Institute, 2022[44]). Reaching net-zero CO_2 leads to stabilising global temperatures, but net-zero GHG is explicitly stated in Article 4.1 of the Paris Agreement and would likely allow to reach declining temperatures in the long-term. Table 4.1 shows that Paris-consistent scenarios reach global net-zero CO_2 emissions around mid-century and global net-zero GHG emissions later in the century. There will, however, be differences in the timing of net zero across countries and sectors.
- **In addition to setting a timing for reaching net-zero emissions, it is crucial that plans and pledges encompass interim emissions reductions targets for halving CO_2 and GHG emissions by 2030-2035 relative to 2019 levels.** Globally, CO_2 and aggregate GHG emissions each need to be reduced by around 40 to 45% in 2030 compared to 2019 levels, if 1.5°C is to stay within reach and dangerous levels of overshoot are to be avoided (Table 4.1). No delayed action after 2030 can reduce the amount of peak warming attained in mid-century, which is determined by emissions levels in this decade. As a consequence, failing to reduce global emissions significantly by 2030 means committing to a high level of overshoot of 1.5°C, even if net-zero emissions are then reached early in the mid-century. Setting net-zero targets by mid-century only is insufficient to leave the door open for the Paris temperature goal, because it may lead to delaying emission reductions until after 2030.

4.2. The criteria framework can help improve the use of climate change mitigation scenarios for measuring alignment with the Paris Agreement

Global climate change mitigation scenarios such as those put forward in this paper are currently used to set benchmarks for measuring the alignment of transition plans and climate policy pledges against the Paris Agreement's mitigation ambition:

- At the governmental level: these scenarios are used to measure the ambition gap between collective emissions implied by NDCs or current governmental policies on the one hand, and emissions pathways required on a global level to reach the Paris Agreement's long-term temperature target on the other hand. This is undertaken by the UNEP emissions gap report (UNEP, 2022[7]), or again by the IPCC assessments (Riahi et al., 2022[18]). Monitoring the level of ambition implied by NDCs in comparison with a global Paris-consistent benchmark is directly relevant for guiding decisions on how to strengthen NDCs (UNEP, 2022[7]).
- In the private and financial sector: for assessing the alignment of investment plans and corporate transition plans with climate goals, corporate strategies are evaluated against benchmark sectoral emissions pathways directly derived from global mitigation scenarios (Noels and Jachnik, 2022[9]).

The framework for assessing the Paris-consistency of scenarios can usefully be applied by different stakeholders in two ways. First, it allows to identify and select scenarios that can be used in such analyses as appropriate benchmarks for Paris ambition. Second, it can help assess whether scenarios currently used as normative benchmarks are consistent with the Paris Agreement's mitigative ambition.

A first application of the criteria framework to the financial sector was conducted by the authors of this paper to assess the Paris-consistency of scenarios currently used for climate-target setting and alignment assessments of finance (Noels et al., 2023[17]). This first application of the framework showed that most of the scenarios currently in use as benchmarks do not fulfil all five criteria and are hence not fully consistent with the mitigation provisions of the Paris Agreement. In particular, very few scenarios in use were consistent with the criteria of limited overshoot of 1.5°C and well-below 2°C. Additionally, almost none of these scenarios reached net-zero GHG emissions during the century (criterion 5).

Such findings confirm that using a complete set of criteria such as the one proposed in this paper is important for selecting Paris-consistent benchmarks and setting the adequate level of ambition in normative use cases of scenarios. The analysis in this paper shows that a thorough science-based approach accounting for all elements of the Paris mitigation objectives is necessary to define Paris-consistent global climate change mitigation scenarios. Ensuring the environmental integrity of decarbonisation benchmarks requires going beyond simplistic, vague or insufficiently ambitious definitions of "net zero" or "2°C" scenarios.

The framework criteria and resulting envelopes will need to be updated overtime to ensure that they encompass the latest scientific information on climate risk and on emissions scenarios, as well as future political, social and technological developments. The framework proposed in this paper and the resulting emissions envelopes reflect the most recent science and scenarios, but this is a dynamic area of research and policymaking. Climate change mitigation scenarios are scientific tools developed to support action in climate change which attempt to best capture aspects of socio-economic development, technological options, and resources as available at the time of scenario development. As such, scenarios are not predictions of the real world which may develop in ways which are not reflected in scenarios. Indeed, models are constantly being updated to incorporate recent societal, technological and policy developments.

4.3. Potential use of the Paris-consistent scenario envelopes to inform net-zero transition policies

Beyond the target setting and alignment assessment use cases, the Paris-consistent scenario envelopes derived in Chapter 3could also inform policy strategies and plans for achieving the net-zero transition and guide climate policy decisions in the short and medium-term to implement the Paris Agreement. Climate change mitigation scenarios are a key tool for understanding the implications of the long-term Paris climate ambition for near-term climate action (Riahi et al., 2022[18]). They show which changes across emitting sectors are required for achieving the Paris climate objectives. While this paper's analysis focused on aggregate-level emissions pathways, scenarios provide a wealth of information on mitigation across emitting sectors and how these can be decarbonised to achieve Paris ambition. Future OECD work could make use of the Paris-consistent scenario envelopes put forward by the present paper to develop robust insights for policymakers in implementing the Paris Agreement and to inform short-term and medium-term policy strategies.

Using envelopes of scenarios rather than a single scenario allows for more robust insights on the transition (Guivarch et al., 2022[5]). A scenario envelope covers multiple possible mitigation strategies and a range of uncertainties stemming from assumptions about future world developments. It is, however, important to note that options identified from a set of scenarios (in the case of this paper, for example, the set of scenarios from the AR6 database) will be limited to the options explored in that ensemble of scenarios. Such scenario sets are not necessarily representative of all possible options and measures that could be put in place to achieve a given temperature outcome (Guivarch et al., 2022[5]).

The Paris-consistent envelopes can directly inform near-term and medium-term policy formulation by delivering benchmarks for the short- and medium-term sectoral and cross-sectoral mitigation measures required to reach the long-term Paris temperature goal. Key benchmarks of the changes across the energy, transport, buildings, agricultural and land use systems required to achieve the Paris Agreement temperature and emissions objectives can be identified using the envelopes. For example, scenario envelopes can be used to derive 2030 and 2050 benchmarks for the deployment of renewables, the deployment of CCS technologies, the phase out of fossil fuels, or again afforestation. These benchmarks could be used as guidance for the formulation of national short-term and mid-term policy strategies.

Such transition benchmarks derived from the Paris-consistent envelopes could be compared against national and global indicators to track the progress of the transition. This would allow to identify where progress is being made and where a lack of progress threatens reaching decarbonisation targets towards the Agreement's goal. Key gaps in the transition and associated policies could be identified, for examples highlighting the need for policies targeting methane emissions reductions in the industrial sector. This could support the identification of policies to strengthen current national plans towards implementing the Paris Agreement.

The envelopes can further inform climate policy strategies by helping to identify feasibility challenges associated with the net-zero transition as well as synergies and trade-offs of mitigation action with sustainability and other policy goals. Ad-hoc studies based on the Paris-consistent scenario envelopes would allow to explore and anticipate a range of implications associated with implementing the Paris Agreement.

References

Ackerman, F., E. Stanton and R. Bueno (2010), “Fat tails, exponents, extreme uncertainty: Simulating catastrophe in DICE”, *Ecological Economics*, Vol. 69/8, pp. 1657-1665, https://doi.org/10.1016/j.ecolecon.2010.03.013. [55]

Allen, M. et al. (2022), “Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets”, *npj Climate and Atmospheric Science*, Vol. 5/1, https://doi.org/10.1038/s41612-021-00226-2. [64]

Arias, P. et al. (2021), *Technical Summary*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896.002. [49]

Armstrong McKay, D. et al. (2022), “Exceeding 1.5°C global warming could trigger multiple climate tipping points”, *Science*, Vol. 377/6611, https://doi.org/10.1126/science.abn7950. [14]

Black, R. et al. (2021), *Taking Stock: A global assessment of net zero targets*. [45]

Boucher, O. et al. (2016), “In the wake of Paris Agreement, scientists must embrace new directions for climate change research”, *Proceedings of the National Academy of Sciences*, Vol. 113/27, pp. 7287-7290, https://doi.org/10.1073/pnas.1607739113. [35]

Brecha, R. et al. (2022), “Institutional decarbonization scenarios evaluated against the Paris Agreement 1.5 °C goal”, *Nature Communications*, Vol. 13/1, https://doi.org/10.1038/s41467-022-31734-1. [53]

Brutschin, E. et al. (2021), “A multidimensional feasibility evaluation of low-carbon scenarios”, *Environmental Research Letters*, Vol. 16/6, p. 064069, https://doi.org/10.1088/1748-9326/abf0ce. [42]

Byers, E. et al. (2022), *AR6 Scenarios Database hosted by IIASA*, International Institute for Applied Systems Analysis, https://doi.org/10.5281/zenodo.5886912. [20]

Cain, M. et al. (2021), “Methane and the Paris Agreement temperature goals”, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 380/2215, https://doi.org/10.1098/rsta.2020.0456. [60]

Canadell, J. et al. (2021), *Global Carbon and other Biogeochemical Cycles and Feedbacks*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896.007. [33]

Drouet, L. et al. (2021), "Net zero-emission pathways reduce the physical and economic risks of climate change", *Nature Climate Change*, Vol. 11/12, pp. 1070-1076, https://doi.org/10.1038/s41558-021-01218-z. [36]

Ehlert, D. and K. Zickfeld (2017), "What determines the warming commitment after cessation of CO2 emissions", *Environmental Research Letters*, Vol. 12/1, p. 015002, https://doi.org/10.1088/1748-9326/aa564a. [34]

Fankhauser, S. et al. (2021), "The meaning of net zero and how to get it right", *Nature Climate Change*, Vol. 12/1, pp. 15-21, https://doi.org/10.1038/s41558-021-01245-w. [47]

Forster, P. et al. (2021), *The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity*, . Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896.009. [51]

Fuglestvedt, J. et al. (2018), "Implications of possible interpretations of 'greenhouse gas balance' in the Paris Agreement", *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 376/2119, p. 20160445, https://doi.org/10.1098/rsta.2016.0445. [11]

Ganti, G. et al. (2023), "Uncompensated claims to fair emission space risk putting Paris Agreement goals out of reach", *Environmental Research Letters*, Vol. 18/2, p. 024040, https://doi.org/10.1088/1748-9326/acb502. [22]

Geden, O. (2016), "An actionable climate target", *Nature Geoscience*, Vol. 9/5, pp. 340-342, https://doi.org/10.1038/ngeo2699. [43]

Guivarch, C. et al. (2022), "Using large ensembles of climate change mitigation scenarios for robust insights", *Nature Climate Change*, Vol. 12/5, pp. 428-435, https://doi.org/10.1038/s41558-022-01349-x. [5]

Hale, T. et al. (2021), "Assessing the rapidly-emerging landscape of net zero targets", *Climate Policy*, Vol. 22/1, pp. 18-29, https://doi.org/10.1080/14693062.2021.2013155. [46]

Huppmann, D. et al. (2018), "A new scenario resource for integrated 1.5 °C research", *Nature Climate Change*, Vol. 8/12, pp. 1027-1030, https://doi.org/10.1038/s41558-018-0317-4. [25]

IEA (2021), *World Energy Outlook 2021*, OECD Publishing, Paris, https://dx.doi.org/10.1787/14fcb638-en. [24]

IPCC (2022), *Annex I: Glossary*, Cambridge University Press, Cambridge, UK and New York, NY, USA, https://doi.org/10.1017/9781009157926.020. [3]

IPCC (2022), *Annex III: Scenarios and modelling methods*, Cambridge University Press, Cambridge, UK and New York, NY, USA, https://doi.org/10.1017/9781009157926.022. [19]

IPCC (2021), *Annex VII: Glossary*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896.022. [2]

IPCC (2021), *Summary for Policymakers*. [32]

IPCC (2018), *Annex I: Glossary*, Cambridge University Press, Cambridge, UK and New York, NY, USA, https://doi.org/10.1017/9781009157940.008. [1]

IPCC (2018), *Global Warming of 1.5 ºC*, https://www.ipcc.ch/sr15. [38]

IPCC (2014), *Climate Change 2014 – Synthesis Report*. [31]

Jeudy-Hugo, S., L. Lo Re and C. Falduto (2021), “Understanding countries’ net-zero emissions targets”*, OECD/IEA Climate Change Expert Group Papers*, No. 2021/03, OECD Publishing, Paris, https://doi.org/10.1787/8d25a20c-en. [48]

Jewell, J. and A. Cherp (2019), “On the political feasibility of climate change mitigation pathways: Is it too late to keep warming below 1.5°C?”, *WIREs Climate Change*, Vol. 11/1, https://doi.org/10.1002/wcc.621. [41]

Krabbe, O. et al. (2015), “Aligning corporate greenhouse-gas emissions targets with climate goals”, *Nature Climate Change*, Vol. 5/12, pp. 1057-1060, https://doi.org/10.1038/nclimate2770. [58]

Lecocq, F. et al. (2022), *Mitigation and development pathways in the near- to mid-term*, Cambridge University Press, Cambridge, UK and New York, NY, USA, https://doi.org/10.1017/9781009157926.006. [8]

Mace, M. (2016), “Mitigation Commitments Under the Paris Agreement and the Way Forward”, *Climate Law*, Vol. 6/1-2, pp. 21-39, https://doi.org/10.1163/18786561-00601002. [28]

Meinshausen, M. et al. (2022), “Realization of Paris Agreement pledges may limit warming just below 2 °C”, *Nature*, Vol. 604/7905, pp. 304-309, https://doi.org/10.1038/s41586-022-04553-z. [6]

Mengel, M. et al. (2018), “Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action”, *Nature Communications*, Vol. 9/1, https://doi.org/10.1038/s41467-018-02985-8. [52]

NewClimate Institute (2022), *Net Zero Stocktake 2022: Assessing the status and trends of net zero target setting across countries, sub-national governments and companies*, NewClimate Institute, Oxford Net Zero, Energy & Climate Intelligence Unit and Data-Driven EnviroLab. [44]

Nisbet, E. et al. (2021), “Atmospheric methane and nitrous oxide: challenges alongthe path to Net Zero”, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 379/2210, p. 20200457, https://doi.org/10.1098/rsta.2020.0457. [61]

Nisbet, E. et al. (2020), “Methane Mitigation: Methods to Reduce Emissions, on the Path to the Paris Agreement”, *Reviews of Geophysics*, Vol. 58/1, https://doi.org/10.1029/2019rg000675. [63]

Noels, J. and R. Jachnik (2022), “Assessing the climate consistency of finance: Taking stock of methodologies and their links to climate mitigation policy objectives”*, OECD Environment Working Papers*, No. 200, OECD Publishing, Paris, https://doi.org/10.1787/d12005e7-en. [9]

Noels, J. et al. (2023), “Climate change mitigation scenarios for financial sector target setting and alignment assessment: A stocktake and analysis of their Paris consistency, practicality, and assumptions”*, OECD Environment Working Papers*, No. 223, OECD Publishing, Paris, https://doi.org/10.1787/bcd25b82-en. [17]

OECD (2022), *Climate Tipping Points: Insights for Effective Policy Action*, OECD Publishing, Paris, https://doi.org/10.1787/abc5a69e-en. [15]

OECD (2021), *Managing Climate Risks, Facing up to Losses and Damages*, OECD Publishing, Paris, https://doi.org/10.1787/55ea1cc9-en. [54]

Ou, Y. et al. (2021), “Deep mitigation of CO2 and non-CO2 greenhouse gases toward 1.5 °C and 2 °C futures”, *Nature Communications*, Vol. 12/1, https://doi.org/10.1038/s41467-021-26509-z. [59]

Pachauri, S. et al. (2022), “Fairness considerations in global mitigation investments”, *Science*, Vol. 378/6624, pp. 1057-1059, https://doi.org/10.1126/science.adf0067. [21]

Palter, J. et al. (2018), “Climate, ocean circulation, and sea level changes under stabilization and overshoot pathways to 1.5 K warming”, *Earth System Dynamics*, Vol. 9/2, pp. 817-828, https://doi.org/10.5194/esd-9-817-2018. [37]

Pekkarinen, V. (2020), “Going beyond CO2”, *Review of European, Comparative & International Environmental Law*, https://doi.org/10.1111/reel.12329. [62]

Rajamani, L. (2016), “AMBITION AND DIFFERENTIATION IN THE 2015 PARIS AGREEMENT: INTERPRETATIVE POSSIBILITIES AND UNDERLYING POLITICS”, *International and Comparative Law Quarterly*, Vol. 65/2, pp. 493-514, https://doi.org/10.1017/s0020589316000130. [10]

Riahi, K. et al. (2022), *Mitigation pathways compatible with long-term goals*, Cambridge University Press, Cambridge, UK and New York, NY, USA, https://doi.org/10.1017/9781009157926.005. [18]

Richters, O. et al. (2022), *NGFS Climate Scenarios Data Set*, https://doi.org/10.5281/zenodo.7198430. [30]

Rogelj, J. et al. (2019), “A new scenario logic for the Paris Agreement long-term temperature goal”, *Nature*, Vol. 573/7774, pp. 357-363, https://doi.org/10.1038/s41586-019-1541-4. [13]

Rogelj, J. et al. (2018), “Scenarios towards limiting global mean temperature increase below 1.5 °C”, *Nature Climate Change*, Vol. 8/4, pp. 325-332, https://doi.org/10.1038/s41558-018-0091-3. [27]

Rogelj, J. et al. (2018), *Mitigation pathways compatible with 1.5°C in the context of sustainable development*, Geneva, Switzerland, IPCC/WMO, http://www.ipcc.ch/report/sr15/. [40]

Schleussner, C. et al. (2022), “An emission pathway classification reflecting the Paris Agreement climate objectives”, *Communications Earth & Environment*, Vol. 3/1, https://doi.org/10.1038/s43247-022-00467-w. [23]

Schleussner, C. et al. (2016), “Science and policy characteristics of the Paris Agreement temperature goal”, *Nature Climate Change*, Vol. 6/9, pp. 827-835, https://doi.org/10.1038/nclimate3096. [29]

Seneviratne, S. et al. (2018), “The many possible climates from the Paris Agreement’s aim of 1.5 °C warming”, *Nature*, Vol. 558/7708, pp. 41-49, https://doi.org/10.1038/s41586-018-0181-4. [12]

Tanaka, K. and B. O’Neill (2018), “The Paris Agreement zero-emissions goal is not always consistent with the 1.5 °C and 2 °C temperature targets”, *Nature Climate Change*, Vol. 8/4, pp. 319-324, https://doi.org/10.1038/s41558-018-0097-x. [50]

UNEP (2022), *Emissions Gap Report 2022: The Closing Window — Climate crisis calls for rapid transformation of societies*. [7]

UNFCCC (2015), *The Paris Agreement*, https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement. [4]

UNFCCC (2010), *Outcome of the Work of the Ad Hoc Working Group on Long-termCooperative Action Under the Convention*. [26]

UNFCCC (1992), *United Nations Framework Convention On Climate Change*, FCCC/INFORMAL/84 GE.05-62220 (E) 200705, Secretariat of the United Nations Framework Convention on Climate Change, Bonn, Germany, https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf (accessed on 28 February 2023). [16]

van Beek, L. et al. (2020), "Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970", *Global Environmental Change*, Vol. 65, p. 102191, https://doi.org/10.1016/j.gloenvcha.2020.102191. [57]

Wagner, G. and M. Weitzman (2018), "Potentially large equilibrium climate sensitivity tail uncertainty", *Economics Letters*, Vol. 168, pp. 144-146, https://doi.org/10.1016/j.econlet.2018.04.036. [56]

Wunderling, N. et al. (2022), "Global warming overshoots increase risks of climate tipping cascades in a network model", *Nature Climate Change*, Vol. 13/1, pp. 75-82, https://doi.org/10.1038/s41558-022-01545-9. [39]

Annex A. GHG and CO_2 emissions pathways in the Paris-consistent scenarios

The tables below report scenario names, corresponding models, as well as 5-yearly GHG and CO_2 emissions values from 2015 to 2100 corresponding to scenarios in the stringent Paris-consistent envelope (Tables A1 and A2), and the less stringent Paris-consistent envelope (Tables A3 and A4). These values correspond to the emissions pathways represented as lines in dark green (stringent envelope) and light green (less stringent envelope) in Figure 3.1 of Chapter 3The scenarios were selected by applying the criteria framework presented in Chapter 3to filter Paris-consistent scenarios from the IPCC AR6 scenarios database. The emissions values for these scenarios are reported in the IPCC AR6 scenarios database (Byers et al., 2022[20]). There are 26 scenarios in the stringent envelope (Tables A1 and A2) and 55 scenarios in the less stringent envelope (Tables A3 and A4). The less stringent envelope includes the scenarios from the stringent envelope.

Table A A.1. GHG emissions in stringent Paris-consistent scenarios ($GtCO_2$-eq)

scenario	model	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
CD-LINKS_NPi2020_400	AIM/CGE 2.1	54,31	57,3	41,77	31,25	21,29	13,7	5,63	0,26	-1,28	-1,7	-1,55	-1,4	-1,3	-1,32	-1,3	-1,14	-1,16	-1,31
1.5C	AIM/Hub-Global 2.0	54,31	58,46	43,09	32,89	22,42	13,94	10,32	8,45	5,61	2,7	-0,16	-0,03	0,09	-0,92	-0,87	-0,8	-0,75	-0,71
SSP1_SPA1_19I_D_LB	IMAGE 3.2	54,31	55,16	50,63	32,7	22,41	14,65	9,58	5,59	4,11	3,39	2,99	2,05	1,84	0,69	0,34	-0,33	-0,49	-1,14
SSP1_SPA1_19I_LIRE_LB	IMAGE 3.2	54,31	55,13	50,93	30,19	17,12	9,66	3,71	-0,15	-1,52	-0,7	-0,62	0,19	0,46	0,12	-0,37	-0,48	-0,85	-1,08
SSP1_SPA1_19I_RE_LB	IMAGE 3.2	54,31	55,16	50,88	32,88	22,15	14,01	8,59	4,65	2,96	2,19	1,63	0,59	0,62	-1	-1,44	-1,88	-2,06	-2,38
SSP2_SPA2_19I_LI	IMAGE 3.2	54,31	55,19	53,29	47,12	32,77	17,19	10,27	4,49	-0,59	-1,9	-1,55	-1,91	-1,08	-1,48	-1,49	-1,33	-1,27	-1,81

scenario	model	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
SSP2-19	MESSAGE-GLOBIOM 1.0	54,31	51,77	41,89	32,05	25,25	18,45	14,11	9,78	6,77	3,77	0,89	-1,99	-4,28	-6,57	-7,59	-8,62	-8,97	-9,32
ADVANCE_2020_1.5C-2100	POLES ADVANCE	54,31	58,51	47,64	33,62	22,9	16,34	11,08	7,01	3,93	1,16	-1,25	-2,72	-4,49	-6,03	-8,62	-9,43	-9,8	-10,29
EMF33_WB2C_nofuel	POLES EMF33	54,31	56,8	44,3	31,9	27,22	22,57	18,46	14,38	10,6	6,84	4,51	2,19	0,79	-0,61	-1,47	-2,32	-3,3	-4,29
ADVANCE_2020_1.5C-2100	REMIND 1.7	54,31	57,8	45,58	32,66	21,82	14,4	8,66	4,15	0,62	-2,18	-3,75	-5,32	-5,66	-5,99	-5,97	-5,95	-6,38	-6,8
CEMICS-1.5-CDR12	REMIND 1.7	54,31	55,27	41,94	27,92	15,81	8,06	3,84	2,08	1,19	0,14	-0,88	-1,91	-2,62	-3,34	-3,64	-3,95	-4,22	-4,48
CEMICS-1.5-CDR20	REMIND 1.7	54,31	55,29	44,74	33,26	24,08	17,78	12,43	7,5	3,06	-0,75	-3,24	-5,77	-6,79	-7,84	-9,02	-10,2	-11,07	-11,94
CEMICS-1.5-CDR8	REMIND 1.7	54,31	55,29	38,68	22,67	8,63	3,72	2,25	1,18	0,72	0,45	0,36	0,28	0,17	0,06	-0,06	-0,19	-0,45	-0,71
CEMICS_HotellingConst_1p5	REMIND 2.1	54,31	54,57	44,12	35,84	27,11	19,85	13,73	7,21	2,2	-1,54	-3,61	-5,69	-6,55	-7,42	-7,91	-8,4	-8,53	-8,66
CEMICS_Linear_1p5	REMIND 2.1	54,31	54,57	43,13	34,42	26,2	19,97	15	9,76	5,8	2,47	-0,08	-2,63	-4,01	-5,38	-6,38	-7,38	-8,15	-8,92
R2p1_SSP1-PkBudg900	REMIND 2.1	54,31	54,69	41,44	33,43	25,68	19,29	14,1	9,27	6,14	3,64	2,04	0,44	-0,54	-1,54	-2,39	-3,25	-4,09	-4,94
R2p1_SSP5-PkBudg900	REMIND 2.1	54,31	54,71	42,31	35,15	27,52	18,75	11,58	5,66	2,99	1,51	0,41	-0,68	-1,51	-2,33	-3,26	-4,18	-5,04	-5,89
SSP2-19	REMIND-MAgPIE 1.5	54,31	56,62	48,58	40,59	28,48	16,43	8,24	0,08	-1,66	-3,4	-4,43	-5,45	-5,99	-6,53	-6,5	-6,47	-7,12	-7,78
PEP_1p5C_red_eff	REMIND-MAgPIE 1.7-3.0	54,31	55,6	37,91	22,14	10,28	4,08	0,81	0,03	-0,38	-0,58	-0,6	-0,62	-0,38	-0,14	-0,34	-0,53	-0,52	-0,52
CEMICS_SSP1-1p5C-fullCDR	REMIND-MAgPIE 2.1-4.2	54,31	54,12	41,59	34,14	26,48	18,22	11,19	8,03	6,27	4,8	3,5	2,21	1,38	0,56	-0,01	-0,58	-1,03	-1,47
SusDev_SSP1-PkBudg900	REMIND-MAgPIE 2.1-4.2	54,31	54,99	41,92	33,04	25,71	20,1	14,83	9,93	6,79	4,24	2,59	0,95	-0,04	-1,05	-1,89	-2,73	-3,58	-4,44
DeepElec_SSP2_def_Budg900	REMIND-MAgPIE 2.1-4.3	54,31	57,23	45,02	31,98	24,22	17,79	11,46	6,58	4,19	2,38	1,18	-0,02	-0,76	-1,49	-1,99	-2,49	-2,77	-3,05
SusDev_SDP-PkBudg1000	REMIND-MAgPIE 2.1-4.2	54,31	55	42,29	32,74	24,77	18,9	14,02	9,52	7,36	5,47	3,93	2,39	1,54	0,69	0,27	-0,15	-0,61	-1,08
SSP4-19	WITCH-GLOBIOM 3.1	54,31	55,51	39,1	22,76	20,41	18,07	14,92	11,78	9,01	6,26	4,16	2,07	0,05	-1,96	-3,15	-4,34	-5,18	-6,03
CD-LINKS_NPi2020_1000	WITCH-GLOBIOM 4.4	54,31	57,78	37,67	28,84	25,26	22,35	19,23	16,5	13,57	10,65	8,88	7,12	5,04	2,97	0,87	-1,23	-2,75	-4,27

scenario	model	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
CD-LINKS_NPi2020_400	WITCH-GLOBIOM 4.4	54,31	57,88	34,65	23,19	18,14	14,42	10,83	8,03	5,55	3,07	1,25	-0,57	-3,21	-5,85	-7,86	-9,87	-9,73	-9,59

Note: Corresponding to the following AR6 database variable: AR6 climate diagnostics|Infilled|Emissions|Kyoto Gases (AR6-GWP100).
Source: Authors and (Byers et al., 2022[20]).

Table A A.2. CO_2 emissions in stringent Paris-consistent scenarios ($GtCO_2$)

scenario	model	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
CD-LINKS_NPi2020_400	AIM/CGE 2.1	39,15	41,73	31,64	23,25	14,46	7,49	0,06	-4,82	-6,41	-6,95	-6,95	-6,94	-6,9	-6,83	-6,8	-6,7	-6,78	-6,76
1.5C	AIM/Hub-Global 2.0	39,15	42,38	32,99	24,46	15,15	7,43	3,95	1,97	-0,92	-3,56	-6,25	-6,27	-6,29	-7,29	-7,31	-7,33	-7,35	-7,37
SSP1_SPA1_19I_D_LB	IMAGE 3.2	39,15	39,81	36,84	22,24	13,59	6,68	2,19	-1,18	-2,52	-3,22	-3,46	-4,2	-4,2	-5,08	-5,18	-5,59	-5,48	-5,88
SSP1_SPA1_19I_LIRE_LB	IMAGE 3.2	39,15	39,79	37,35	20,14	8,91	2,24	-2,97	-6,24	-7,46	-6,54	-6,22	-5,24	-4,8	-4,96	-5,24	-5,17	-5,31	-5,36
SSP1_SPA1_19I_RE_LB	IMAGE 3.2	39,15	39,81	37,08	22,44	13,39	6,08	1,27	-2,07	-3,57	-4,26	-4,65	-5,5	-5,28	-6,62	-6,8	-7	-6,91	-6,99
SSP2_SPA2_19I_LI	IMAGE 3.2	39,15	39,81	39,37	33,97	20,75	8,33	2,71	-2,46	-7,19	-8,41	-8,02	-8,26	-7,33	-7,57	-7,46	-7,12	-6,87	-7,24
SSP2-19	MESSAGE-GLOBIOM 1.0	39,15	36,57	28,15	19,72	13,86	8	4,31	0,61	-1,87	-4,35	-6,7	-9,05	-10,93	-12,81	-13,56	-14,3	-14,46	-14,62
ADVANCE_2020_1.5C-2100	POLES ADVANCE	39,15	43,04	37,14	25,97	16,47	10,41	5,43	1,56	-1,37	-4	-6,3	-7,69	-9,4	-10,88	-13,44	-14,25	-14,6	-15,07
EMF33_WB2C_nofuel	POLES EMF33	39,15	40,7	32,52	24,35	20,48	16,62	13,09	9,58	6,19	2,81	0,8	-1,2	-2,46	-3,71	-4,5	-5,28	-6,18	-7,09
ADVANCE_2020_1.5C-2100	REMIND 1.7	39,15	41,53	32,75	21,81	12,12	5,26	-0,28	-4,49	-8,14	-10,99	-12,59	-14,19	-14,44	-14,69	-14,49	-14,3	-14,48	-14,66
CEMICS-1.5-CDR12	REMIND 1.7	39,15	39,94	29,7	17,54	6,19	-1,23	-5,32	-6,83	-7,86	-8,98	-10,03	-11,1	-11,74	-12,39	-12,53	-12,67	-12,65	-12,63
CEMICS-1.5-CDR20	REMIND 1.7	39,15	39,94	32,12	22,15	14,09	8,3	3,11	-1,63	-6,27	-10,2	-12,72	-15,26	-16,14	-17,05	-18	-18,95	-19,53	-20,12
CEMICS-1.5-CDR8	REMIND 1.7	39,15	39,94	26,77	12,5	-0,85	-5,5	-6,87	-7,72	-8,33	-8,65	-8,75	-8,86	-8,87	-8,89	-8,85	-8,81	-8,78	-8,75
CEMICS_HotellingConst_1p5	REMIND 2.1	39,15	39,37	31,64	24,64	16,9	10,19	4,32	-2	-7,13	-10,87	-12,86	-14,85	-15,53	-16,21	-16,43	-16,65	-16,61	-16,57

scenario	model	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
CEMICS_Linear_1p5	REMIND 2.1	39,15	39,37	30,72	23,32	16,09	10,37	5,6	0,56	-3,53	-6,9	-9,38	-11,86	-13,03	-14,2	-14,93	-15,66	-16,25	-16,84
R2p1_SSP1-PkBudg900	REMIND 2.1	39,15	39,5	29,56	22,7	15,82	9,99	5,43	1,34	-1,37	-3,54	-4,72	-5,89	-6,46	-7,02	-7,54	-8,06	-8,63	-9,2
R2p1_SSP5-PkBudg900	REMIND 2.1	39,15	39,5	30,76	25,28	18,21	9,57	2,66	-2,96	-5,7	-7,11	-8,04	-8,96	-9,51	-10,06	-10,66	-11,26	-11,86	-12,46
SSP2-19	REMIND-MAgPIE 1.5	39,15	41,45	35,72	30,01	18,6	7,23	-0,73	-8,66	-10,21	-11,75	-12,74	-13,72	-14,14	-14,56	-14,3	-14,04	-14,44	-14,84
PEP_1p5C_red_eff	REMIND-MAgPIE 1.7-3.0	39,15	39,81	26,69	12,55	1,56	-4,76	-7,46	-8,11	-8,26	-8,43	-8,39	-8,35	-7,98	-7,61	-7,58	-7,55	-7,25	-6,95
CEMICS_SSP1-1p5C-fullCDR	REMIND-MAgPIE 2.1-4.2	39,15	39,1	29,94	24,29	17,6	10	3,4	0,8	-0,74	-1,91	-2,78	-3,66	-4,08	-4,51	-4,74	-4,97	-5,15	-5,33
SusDev_SSP1-PkBudg900	REMIND-MAgPIE 2.1-4.2	39,15	39,8	30,05	22,24	15,75	10,68	6,05	1,93	-0,76	-2,96	-4,18	-5,4	-5,98	-6,55	-7,04	-7,53	-8,11	-8,69
DeepElec_SSP2_def_Budg900	REMIND-MAgPIE 2.1-4.3	39,15	41,7	32,33	21,4	14,49	8,31	2,16	-2,56	-5,05	-6,87	-8,04	-9,2	-9,78	-10,36	-10,63	-10,89	-11,04	-11,18
SusDev_SDP-PkBudg1000	REMIND-MAgPIE 2.1-4.2	39,15	39,8	30,81	23,84	17,5	12,99	9,18	5,67	3,62	1,85	0,43	-0,98	-1,73	-2,47	-2,81	-3,15	-3,52	-3,88
SSP4-19	WITCH-GLOBIOM 3.1	39,15	40,14	26,51	12,94	11,15	9,37	6,77	4,18	1,96	-0,24	-1,93	-3,61	-5,46	-7,3	-8,35	-9,4	-10,12	-10,84
CD-LINKS_NPi2020_1000	WITCH-GLOBIOM 4.4	39,15	41,97	29,26	21,7	18,7	16,15	13,38	10,96	8,19	5,43	3,84	2,25	0,35	-1,54	-3,52	-5,49	-6,76	-8,04
CD-LINKS_NPi2020_400	WITCH-GLOBIOM 4.4	39,15	41,97	26,3	16,29	11,64	8,19	4,84	2,3	-0,07	-2,43	-4,09	-5,75	-8,19	-10,62	-12,52	-14,41	-14,19	-13,96

Note: Corresponding to the following AR6 database variable: AR6 climate diagnostics|Infilled|Emissions|CO2.
Source: Authors and (Byers et al., 2022[20]).

Table A A.3. GHG emissions in less stringent Paris-consistent scenarios ($GtCO_2$-eq)

scenario	model	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
CD-LINKS_NPi2020_400	AIM/CGE 2.1	54,31	57,3	41,77	31,25	21,29	13,7	5,63	0,26	-1,28	-1,7	-1,55	-1,4	-1,3	-1,32	-1,3	-1,14	-1,16	-1,31
1.5C	AIM/Hub-Global 2.0	54,31	58,46	43,09	32,89	22,42	13,94	10,32	8,45	5,61	2,7	-0,16	-0,03	0,09	-0,92	-0,87	-0,8	-0,75	-0,71

scenario	model	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Ratchet-1.5-limCDR-noOS	C-ROADS-5.005	54,31	53,29	42,35	23,57	11,24	3,62	-0,77	-3,2	-3,84	-3,74	-3,42	-2,92	-2,35	-1,71	-0,8	0,09	0,9	1,66
Ratchet-1.5-noCDR	C-ROADS-5.005	54,31	53,44	52,56	32,4	19,63	11,69	7,07	4,35	3,15	2,86	2,67	2,53	2,38	2,25	2,37	2,49	2,57	2,64
Ratchet-1.5-noCDR-noOS	C-ROADS-5.005	54,31	53,35	41,02	21,51	11,11	5,9	3,65	3,03	2,85	2,73	2,61	2,5	2,37	2,24	2,37	2,5	2,58	2,65
R_MAC_35_n8	GCAM 5.3	54,31	56,2	36,66	20,58	4,19	4,34	4,21	4,14	3,84	3,72	3,62	3,51	3,41	3,31	3,3	3,26	3,21	3,13
R_MAC_40_n8	GCAM 5.3	54,31	56,2	40,93	28,68	16,7	4,31	4,21	4,13	3,83	3,71	3,62	3,52	3,42	3,31	3,29	3,25	3,19	3,12
R_MAC_45_n8	GCAM 5.3	54,31	56,2	43,48	33,87	24,06	14,35	4,2	4,14	3,83	3,71	3,62	3,52	3,42	3,31	3,29	3,24	3,18	3,09
SSP1_SPA1_19I_D_LB	IMAGE 3.2	54,31	55,16	50,63	32,7	22,41	14,65	9,58	5,59	4,11	3,39	2,99	2,05	1,84	0,69	0,34	-0,33	-0,49	-1,14
SSP1_SPA1_19I_LIRE_LB	IMAGE 3.2	54,31	55,13	50,93	30,19	17,12	9,66	3,71	-0,15	-1,52	-0,7	-0,62	0,19	0,46	0,12	-0,37	-0,48	-0,85	-1,08
SSP1_SPA1_19I_RE_LB	IMAGE 3.2	54,31	55,16	50,88	32,88	22,15	14,01	8,59	4,65	2,96	2,19	1,63	0,59	0,62	-1	-1,44	-1,88	-2,06	-2,38
SSP2_SPA1_19I_D_LB	IMAGE 3.2	54,31	55,25	51,31	35,96	26,3	19,8	14,46	9,56	7,69	6,28	6,03	5,1	5,34	4,39	4,67	3,55	3,77	3,08
SSP2_SPA1_19I_LIRE_LB	IMAGE 3.2	54,31	55,19	50,55	31,71	19,76	13,01	7,53	3,29	1,86	2,51	2,71	3,26	3,67	3,08	2,97	3,09	3	3,05
SSP2_SPA2_19I_LI	IMAGE 3.2	54,31	55,19	53,29	47,12	32,77	17,19	10,27	4,49	-0,59	-1,9	-1,55	-1,91	-1,08	-1,48	-1,49	-1,33	-1,27	-1,81
ADVANCE_2020_1.5C-2100	MESSAGE-GLOBIOM 1.0	54,31	51,51	38,71	25,96	20,78	15,61	11,82	8,05	5,13	2,21	-0,67	-3,54	-6,13	-8,71	-9,36	-10,01	-10,18	-10,36
EMF33_1.5C_cost100	MESSAGE-GLOBIOM 1.0	54,31	52,19	37,26	22,48	17,35	12,24	8,4	4,57	0,07	-4,43	-5,62	-6,81	-7,85	-8,89	-9,41	-9,94	-10,13	-10,31
EMF33_1.5C_full	MESSAGE-GLOBIOM 1.0	54,31	52,19	37,27	22,5	17,39	12,28	8,44	4,61	0,03	-4,54	-5,7	-6,86	-7,89	-8,91	-9,43	-9,95	-10,12	-10,28
SSP2-19	MESSAGE-GLOBIOM 1.0	54,31	51,77	41,89	32,05	25,25	18,45	14,11	9,78	6,77	3,77	0,89	-1,99	-4,28	-6,57	-7,59	-8,62	-8,97	-9,32
ADVANCE_2020_1.5C-2100	POLES ADVANCE	54,31	58,51	47,64	33,62	22,9	16,34	11,08	7,01	3,93	1,16	-1,25	-2,72	-4,49	-6,03	-8,62	-9,43	-9,8	-10,29
EMF33_WB2C_cost100	POLES EMF33	54,31	56,82	44,47	32,21	27,69	23,18	18,93	14,69	10,87	7,05	4,67	2,3	0,83	-0,63	-1,47	-2,31	-3,32	-4,34
EMF33_WB2C_full	POLES EMF33	54,31	56,82	44,73	32,74	28,25	23,79	19,39	15,01	11,23	7,47	5,1	2,74	1,11	-0,52	-1,36	-2,21	-3,28	-4,35
EMF33_WB2C_nofuel	POLES EMF33	54,31	56,8	44,3	31,9	27,22	22,57	18,46	14,38	10,6	6,84	4,51	2,19	0,79	-0,61	-1,47	-2,32	-3,3	-4,29
ADVANCE_2020_1.5C-2100	REMIND 1.7	54,31	57,8	45,58	32,66	21,82	14,4	8,66	4,15	0,62	-2,18	-3,75	-5,32	-5,66	-5,99	-5,97	-5,95	-6,38	-6,8

scenario	model	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
CEMICS-1.5-CDR12	REMIND 1.7	54,31	55,27	41,94	27,92	15,81	8,06	3,84	2,08	1,19	0,14	-0,88	-1,91	-2,62	-3,34	-3,64	-3,95	-4,22	-4,48
CEMICS-1.5-CDR20	REMIND 1.7	54,31	55,29	44,74	33,26	24,08	17,78	12,43	7,5	3,06	-0,75	-3,24	-5,77	-6,79	-7,84	-9,02	-10,2	-11,07	-11,94
CEMICS-1.5-CDR8	REMIND 1.7	54,31	55,29	38,68	22,67	8,63	3,72	2,25	1,18	0,72	0,45	0,36	0,28	0,17	0,06	-0,06	-0,19	-0,45	-0,71
CEMICS-2.0-CDR8	REMIND 1.7	54,31	55,26	44,49	33,07	24,68	19,31	15,18	12,28	10,69	9,25	7,96	6,66	5,42	4,17	2,69	1,21	0,54	-0,13
CEMICS_GDPgrowth_1p5	REMIND 2.1	54,31	54,88	43,08	33,95	26,64	21,09	16,54	11,63	8,05	5,18	2,99	0,81	-0,62	-2,05	-3,09	-4,14	-5,18	-6,22
CEMICS_HotellingConst_1p5	REMIND 2.1	54,31	54,57	44,12	35,84	27,11	19,85	13,73	7,21	2,2	-1,54	-3,61	-5,69	-6,55	-7,42	-7,91	-8,4	-8,53	-8,66
CEMICS_Linear_1p5	REMIND 2.1	54,31	54,57	43,13	34,42	26,2	19,97	15	9,76	5,8	2,47	-0,08	-2,63	-4,01	-5,38	-6,38	-7,38	-8,15	-8,92
R2p1_SSP1-PkBudg900	REMIND 2.1	54,31	54,69	41,44	33,43	25,68	19,29	14,1	9,27	6,14	3,64	2,04	0,44	-0,54	-1,54	-2,39	-3,25	-4,09	-4,94
R2p1_SSP5-PkBudg900	REMIND 2.1	54,31	54,71	42,31	35,15	27,52	18,75	11,58	5,66	2,99	1,51	0,41	-0,68	-1,51	-2,33	-3,26	-4,18	-5,04	-5,89
SSP2-19	REMIND-MAgPIE 1.5	54,31	56,62	48,58	40,59	28,48	16,43	8,24	0,08	-1,66	-3,4	-4,43	-5,45	-5,99	-6,53	-6,5	-6,47	-7,12	-7,78
CD-LINKS_NPi2020_400	REMIND-MAgPIE 1.7-3.0	54,31	56,21	44,1	33,3	23,85	17,14	11,1	6,58	2,2	-1,01	-2,91	-4,8	-5,7	-6,59	-7,25	-7,91	-8,66	-9,42
PEP_1p5C_full_eff	REMIND-MAgPIE 1.7-3.0	54,31	56	44,67	34,47	24,58	17,58	10,93	6,02	1,65	-1,4	-3,37	-5,34	-6,27	-7,21	-7,76	-8,31	-9,01	-9,7
PEP_1p5C_red_eff	REMIND-MAgPIE 1.7-3.0	54,31	55,6	37,91	22,14	10,28	4,08	0,81	0,03	-0,38	-0,58	-0,6	-0,62	-0,38	-0,14	-0,34	-0,53	-0,52	-0,52
PEP_2C_red_eff	REMIND-MAgPIE 1.7-3.0	54,31	55,96	44,6	34,02	24,32	18,1	12,94	9,78	7,32	6,05	5,37	4,69	4,87	5,05	5,19	5,33	5,1	4,86
CEMICS_SSP1-1p5C-fullCDR	REMIND-MAgPIE 2.1-4.2	54,31	54,12	41,59	34,14	26,48	18,22	11,19	8,03	6,27	4,8	3,5	2,21	1,38	0,56	-0,01	-0,58	-1,03	-1,47
CEMICS_SSP1-1p5C-minCDR	REMIND-MAgPIE 2.1-4.2	54,31	54,18	39,73	30,97	23,77	17,31	12,8	9,79	8,4	7,25	6,42	5,58	4,98	4,38	3,87	3,36	3,03	2,7
CEMICS_SSP2-1p5C-fullCDR	REMIND-MAgPIE 2.1-4.2	54,31	54,43	43,16	35,53	26,82	17,97	12,11	9,36	7,98	7,43	6,93	6,43	6,24	6,05	5,86	5,67	5,32	4,96
EN_NPi2020_300f	REMIND-MAgPIE 2.1-4.2	54,31	55,08	42,43	33,25	26,41	21,66	17,49	12,96	10,1	7,92	6,31	4,71	2,44	0,19	-2,38	-4,96	-6,57	-8,18
NGFS2_Divergent Net Zero Policies	REMIND-MAgPIE 2.1-4.2	54,31	54,87	41,29	29,04	20,96	15,72	12,16	9,44	8,02	7,01	6,47	5,94	5,65	5,37	5,04	4,71	4,45	4,19

scenario	model	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
NGFS2_Net-Zero 2050 - IPD-95th	REMIND-MAgPIE 2.1-4.2	54,31	54,17	38,56	27,11	20,45	15,65	11,73	8,7	7,29	6,66	6,47	6,28	6,17	6,05	5,82	5,6	5,3	5
SusDev_SSP1-PkBudg900	REMIND-MAgPIE 2.1-4.2	54,31	54,99	41,92	33,04	25,71	20,1	14,83	9,93	6,79	4,24	2,59	0,95	-0,04	-1,05	-1,89	-2,73	-3,58	-4,44
DeepElec_SSP2_def_Budg900	REMIND-MAgPIE 2.1-4.3	54,31	57,23	45,02	31,98	24,22	17,79	11,46	6,58	4,19	2,38	1,18	-0,02	-0,76	-1,49	-1,99	-2,49	-2,77	-3,05
SusDev_SDP-PkBudg1000	REMIND-MAgPIE 2.1-4.2	54,31	55	42,29	32,74	24,77	18,9	14,02	9,52	7,36	5,47	3,93	2,39	1,54	0,69	0,27	-0,15	-0,61	-1,08
EN_NPi2020_400f	WITCH 5.0	54,31	55,09	32,99	26,47	21,59	18,51	14,82	11,65	9,14	6,65	4,83	2,61	-0,16	-2,28	-3,63	-5,21	-6,63	-8,18
EN_NPi2020_450	WITCH 5.0	54,31	55,09	29,85	21,37	15,19	11,48	8,28	5,91	4,63	4,66	4,62	4,57	4,49	4,39	4,26	4,15	4,08	3,93
EN_NPi2020_450f	WITCH 5.0	54,31	55,09	33,44	26,98	22,26	19,4	15,63	12,38	9,82	7,37	5,43	3,29	0,74	-1,59	-3,04	-4,59	-6,01	-7,59
EN_NPi2020_500	WITCH 5.0	54,31	55,09	31,09	23,66	17,28	13,15	10,07	7,61	5,6	4,69	4,61	4,55	4,5	4,53	4,42	4,32	4,22	4,13
EN_NPi2020_500f	WITCH 5.0	54,31	55,09	34,14	27,56	22,92	20,12	16,63	13,27	10,57	8,02	6,04	3,89	1,37	-0,69	-2,45	-4,07	-5,5	-7,07
SSP1-19	WITCH-GLOBIOM 3.1	54,31	53,34	36,78	20,31	18,14	15,98	13,23	10,49	8,08	5,67	3,74	1,82	-0,08	-1,97	-3,13	-4,29	-4,63	-4,96
SSP4-19	WITCH-GLOBIOM 3.1	54,31	55,51	39,1	22,76	20,41	18,07	14,92	11,78	9,01	6,26	4,16	2,07	0,05	-1,96	-3,15	-4,34	-5,18	-6,03
CD-LINKS_NPi2020_1000	WITCH-GLOBIOM 4.4	54,31	57,78	37,67	28,84	25,26	22,35	19,23	16,5	13,57	10,65	8,88	7,12	5,04	2,97	0,87	-1,23	-2,75	-4,27
CD-LINKS_NPi2020_400	WITCH-GLOBIOM 4.4	54,31	57,88	34,65	23,19	18,14	14,42	10,83	8,03	5,55	3,07	1,25	-0,57	-3,21	-5,85	-7,86	-9,87	-9,73	-9,59

Note: Corresponding to the following AR6 database variable: AR6 climate diagnostics|Infilled|Emissions|Kyoto Gases (AR6-GWP_{100}).
Source: Authors and (Byers et al., 2022[20]).

Table A A.4. CO_2 emissions in less stringent Paris-consistent scenarios ($GtCO_2$)

scenario	model	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
CD-LINKS_NPi2020_400	AIM/CGE 2.1	39,15	41,73	31,64	23,25	14,46	7,49	0,06	-4,82	-6,41	-6,95	-6,95	-6,94	-6,90	-6,83	-6,80	-6,70	-6,78	-6,76
1.5C	AIM/Hub-Global 2.0	39,15	42,38	32,99	24,46	15,15	7,43	3,95	1,97	-0,92	-3,56	-6,25	-6,27	-6,29	-7,29	-7,31	-7,33	-7,35	-7,37
Ratchet-1.5-limCDR-noOS	C-ROADS-5.005	39,15	38,38	29,73	12,84	1,43	-5,36	-9,16	-11,03	-11,37	-10,98	-10,33	-9,51	-8,59	-7,62	-6,63	-5,66	-4,73	-3,85

scenario	model	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
Ratchet-1.5-noCDR	C-ROADS-5.005	39,15	38,51	37,96	21,61	9,80	2,69	-1,33	-3,48	-4,38	-4,38	-4,24	-4,06	-3,86	-3,66	-3,45	-3,25	-3,06	-2,87
Ratchet-1.5-noCDR-noOS	C-ROADS-5.005	39,15	38,46	28,70	10,83	1,33	-3,07	-4,74	-4,80	-4,69	-4,52	-4,31	-4,10	-3,88	-3,67	-3,46	-3,26	-3,06	-2,88
R_MAC_35_n8	GCAM 5.3	39,15	40,44	23,46	7,82	-7,81	-7,81	-7,82	-7,83	-7,84	-7,84	-7,85	-7,86	-7,86	-7,87	-7,88	-7,89	-7,90	-7,90
R_MAC_40_n8	GCAM 5.3	39,15	40,44	27,37	15,64	3,90	-7,81	-7,82	-7,83	-7,84	-7,84	-7,85	-7,86	-7,86	-7,87	-7,88	-7,89	-7,90	-7,90
R_MAC_45_n8	GCAM 5.3	39,15	40,44	29,72	20,33	10,93	1,55	-7,82	-7,83	-7,84	-7,84	-7,85	-7,86	-7,86	-7,87	-7,88	-7,89	-7,90	-7,90
SSP1_SPA1_19I_D_LB	IMAGE 3.2	39,15	39,81	36,84	22,24	13,59	6,68	2,19	-1,18	-2,52	-3,22	-3,46	-4,20	-4,20	-5,08	-5,18	-5,59	-5,48	-5,88
SSP1_SPA1_19I_LIRE_LB	IMAGE 3.2	39,15	39,79	37,35	20,14	8,91	2,24	-2,97	-6,24	-7,46	-6,54	-6,22	-5,24	-4,80	-4,96	-5,24	-5,17	-5,31	-5,36
SSP1_SPA1_19I_RE_LB	IMAGE 3.2	39,15	39,81	37,08	22,44	13,39	6,08	1,27	-2,07	-3,57	-4,26	-4,65	-5,50	-5,28	-6,62	-6,80	-7,00	-6,91	-6,99
SSP2_SPA1_19I_D_LB	IMAGE 3.2	39,15	39,86	37,26	24,61	16,40	10,60	5,73	1,25	-0,59	-2,01	-2,17	-2,97	-2,62	-3,43	-3,03	-3,91	-3,50	-3,93
SSP2_SPA1_19I_LIRE_LB	IMAGE 3.2	39,15	39,81	36,85	21,22	11,07	5,15	0,40	-3,28	-4,51	-3,81	-3,42	-2,72	-2,20	-2,65	-2,60	-2,36	-2,26	-2,03
SSP2_SPA2_19I_LI	IMAGE 3.2	39,15	39,81	39,37	33,97	20,75	8,33	2,71	-2,46	-7,19	-8,41	-8,02	-8,26	-7,33	-7,57	-7,46	-7,12	-6,87	-7,24
ADVANCE_2020_1.5C-2100	MESSAGE-GLOBIOM 1.0	39,15	36,39	25,65	14,90	10,52	6,14	2,96	-0,22	-2,66	-5,10	-7,54	-9,99	-12,30	-14,61	-15,10	-15,58	-15,66	-15,74
EMF33_1.5C_cost100	MESSAGE-GLOBIOM 1.0	39,15	36,92	24,51	12,09	7,57	3,04	-0,22	-3,49	-7,47	-11,44	-12,32	-13,19	-13,97	-14,75	-15,13	-15,52	-15,61	-15,70
EMF33_1.5C_full	MESSAGE-GLOBIOM 1.0	39,15	36,92	24,53	12,14	7,61	3,08	-0,19	-3,46	-7,51	-11,56	-12,40	-13,25	-14,01	-14,78	-15,16	-15,53	-15,60	-15,67
SSP2-19	MESSAGE-GLOBIOM 1.0	39,15	36,57	28,15	19,72	13,86	8,00	4,31	0,61	-1,87	-4,35	-6,70	-9,05	-10,93	-12,81	-13,56	-14,30	-14,46	-14,62
ADVANCE_2020_1.5C-2100	POLES ADVANCE	39,15	43,04	37,14	25,97	16,47	10,41	5,43	1,56	-1,37	-4,00	-6,30	-7,69	-9,40	-10,88	-13,44	-14,25	-14,60	-15,07
EMF33_WB2C_cost100	POLES EMF33	39,15	40,71	32,67	24,63	20,92	17,21	13,54	9,89	6,40	2,92	0,78	-1,35	-2,59	-3,83	-4,57	-5,32	-6,24	-7,16
EMF33_WB2C_full	POLES EMF33	39,15	40,71	32,90	25,10	21,36	17,63	13,82	10,02	6,52	3,02	0,87	-1,27	-2,62	-3,96	-4,67	-5,38	-6,37	-7,35
EMF33_WB2C_nofuel	POLES EMF33	39,15	40,70	32,52	24,35	20,48	16,62	13,09	9,58	6,19	2,81	0,80	-1,20	-2,46	-3,71	-4,50	-5,28	-6,18	-7,09
ADVANCE_2020_1.5C-2100	REMIND 1.7	39,15	41,53	32,75	21,81	12,12	5,26	-0,28	-4,49	-8,14	-10,99	-12,59	-14,19	-14,44	-14,69	-14,49	-14,30	-14,48	-14,66
CEMICS-1.5-CDR12	REMIND 1.7	39,15	39,94	29,70	17,54	6,19	-1,23	-5,32	-6,83	-7,86	-8,98	-10,03	-11,10	-11,74	-12,39	-12,53	-12,67	-12,65	-12,63

scenario	model	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
CEMICS-1.5-CDR20	REMIND 1.7	39,15	39,94	32,12	22,15	14,09	8,30	3,11	-1,63	-6,27	-10,20	-12,72	-15,26	-16,14	-17,05	-18,00	-18,95	-19,53	-20,12
CEMICS-1.5-CDR8	REMIND 1.7	39,15	39,94	26,77	12,50	-0,85	-5,50	-6,87	-7,72	-8,33	-8,65	-8,75	-8,86	-8,87	-8,89	-8,85	-8,81	-8,78	-8,75
CEMICS-2.0-CDR8	REMIND 1.7	39,15	39,94	31,95	22,08	14,75	9,83	5,90	3,26	1,55	0,06	-1,24	-2,57	-3,72	-4,89	-6,22	-7,54	-7,96	-8,38
CEMICS_GDPgrowth_1p5	REMIND 2.1	39,15	39,37	30,12	22,34	15,90	10,79	6,38	1,63	-2,10	-5,02	-7,18	-9,34	-10,64	-11,94	-12,77	-13,60	-14,52	-15,43
CEMICS_HotellingConst_1p5	REMIND 2.1	39,15	39,37	31,64	24,64	16,90	10,19	4,32	-2,00	-7,13	-10,87	-12,86	-14,85	-15,53	-16,21	-16,43	-16,65	-16,61	-16,57
CEMICS_Linear_1p5	REMIND 2.1	39,15	39,37	30,72	23,32	16,09	10,37	5,60	0,56	-3,53	-6,90	-9,38	-11,86	-13,03	-14,20	-14,93	-15,66	-16,25	-16,84
R2p1_SSP1-PkBudg900	REMIND 2.1	39,15	39,50	29,56	22,70	15,82	9,99	5,43	1,34	-1,37	-3,54	-4,72	-5,89	-6,46	-7,02	-7,54	-8,06	-8,63	-9,20
R2p1_SSP5-PkBudg900	REMIND 2.1	39,15	39,50	30,76	25,28	18,21	9,57	2,66	-2,96	-5,70	-7,11	-8,04	-8,96	-9,51	-10,06	-10,66	-11,26	-11,86	-12,46
SSP2-19	REMIND-MAgPIE 1.5	39,15	41,45	35,72	30,01	18,60	7,23	-0,73	-8,66	-10,21	-11,75	-12,74	-13,72	-14,14	-14,56	-14,30	-14,04	-14,44	-14,84
CD-LINKS_NPi2020_400	REMIND-MAgPIE 1.7-3.0	39,15	40,67	32,13	22,91	14,66	8,09	2,59	-1,95	-6,11	-9,32	-11,19	-13,05	-13,84	-14,63	-15,05	-15,48	-15,96	-16,44
PEP_1p5C_full_eff	REMIND-MAgPIE 1.7-3.0	39,15	40,27	32,40	23,79	15,30	8,51	2,39	-2,52	-6,67	-9,71	-11,64	-13,57	-14,39	-15,21	-15,53	-15,85	-16,27	-16,69
PEP_1p5C_red_eff	REMIND-MAgPIE 1.7-3.0	39,15	39,81	26,69	12,55	1,56	-4,76	-7,46	-8,11	-8,26	-8,43	-8,39	-8,35	-7,98	-7,61	-7,58	-7,55	-7,25	-6,95
PEP_2C_red_eff	REMIND-MAgPIE 1.7-3.0	39,15	40,16	31,98	23,47	15,28	9,20	4,57	1,45	-0,78	-2,00	-2,57	-3,15	-2,84	-2,54	-2,16	-1,78	-1,70	-1,62
CEMICS_SSP1-1p5C-fullCDR	REMIND-MAgPIE 2.1-4.2	39,15	39,10	29,94	24,29	17,60	10,00	3,40	0,80	-0,74	-1,91	-2,78	-3,66	-4,08	-4,51	-4,74	-4,97	-5,15	-5,33
CEMICS_SSP1-1p5C-minCDR	REMIND-MAgPIE 2.1-4.2	39,15	39,10	28,28	21,45	15,08	9,22	5,10	2,64	1,48	0,62	0,20	-0,21	-0,42	-0,63	-0,81	-0,99	-1,05	-1,11
CEMICS_SSP2-1p5C-fullCDR	REMIND-MAgPIE 2.1-4.2	39,15	39,34	30,83	24,83	16,99	8,59	2,91	0,35	-1,10	-1,70	-2,12	-2,55	-2,56	-2,56	-2,49	-2,42	-2,62	-2,81
EN_NPi2020_300f	REMIND-MAgPIE 2.1-4.2	39,15	39,82	30,58	22,76	16,49	12,09	8,13	3,89	1,01	-1,14	-2,69	-4,23	-6,29	-8,35	-10,67	-12,99	-14,46	-15,93
NGFS2_Divergent Net Zero Policies	REMIND-MAgPIE 2.1-4.2	39,15	39,72	28,61	18,60	11,54	6,59	3,19	0,66	-0,85	-1,86	-2,31	-2,76	-2,87	-2,99	-3,08	-3,18	-3,29	-3,40

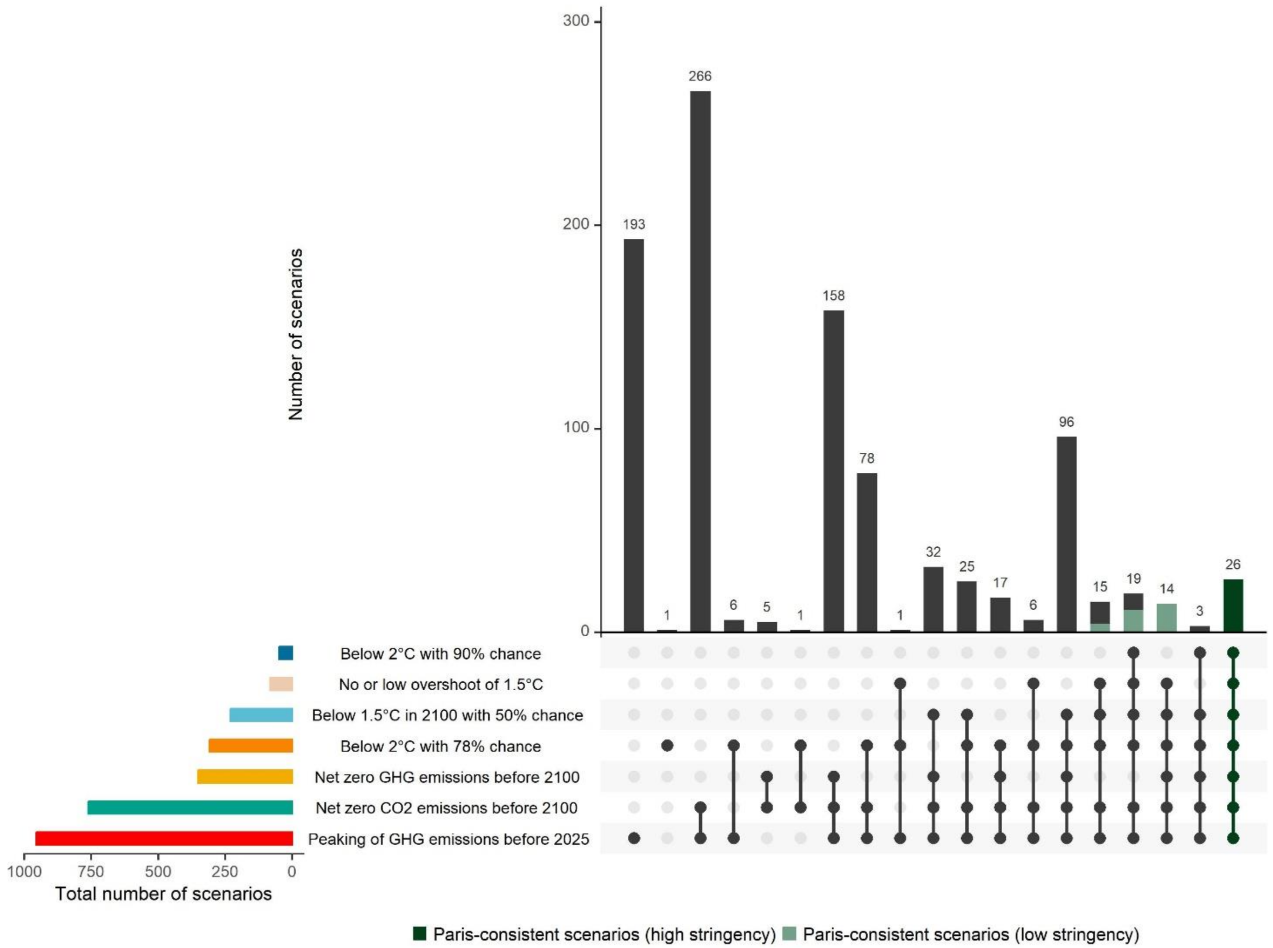
scenario	model	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
NGFS2_Net-Zero 2050 - IPD-95th	REMIND-MAgPIE 2.1-4.2	39,15	39,67	27,60	17,27	11,17	6,57	2,80	-0,02	-1,50	-2,12	-2,22	-2,32	-2,25	-2,18	-2,15	-2,12	-2,26	-2,40
SusDev_SSP1-PkBudg900	REMIND-MAgPIE 2.1-4.2	39,15	39,80	30,05	22,24	15,75	10,68	6,05	1,93	-0,76	-2,96	-4,18	-5,40	-5,98	-6,55	-7,04	-7,53	-8,11	-8,69
DeepElec_SSP2_def_Budg900	REMIND-MAgPIE 2.1-4.3	39,15	41,70	32,33	21,40	14,49	8,31	2,16	-2,56	-5,05	-6,87	-8,04	-9,20	-9,78	-10,36	-10,63	-10,89	-11,04	-11,18
SusDev_SDP-PkBudg1000	REMIND-MAgPIE 2.1-4.2	39,15	39,80	30,81	23,84	17,50	12,99	9,18	5,67	3,62	1,85	0,43	-0,98	-1,73	-2,47	-2,81	-3,15	-3,52	-3,88
EN_NPi2020_400f	WITCH 5.0	39,15	39,25	24,91	19,50	15,07	12,22	8,73	5,73	3,25	0,79	-0,98	-3,15	-5,84	-7,88	-9,17	-10,66	-11,99	-13,47
EN_NPi2020_450	WITCH 5.0	39,15	39,25	22,38	14,70	8,82	5,32	2,28	0,08	-1,19	-1,17	-1,20	-1,23	-1,26	-1,30	-1,35	-1,38	-1,37	-1,43
EN_NPi2020_450f	WITCH 5.0	39,15	39,25	25,27	19,92	15,72	13,09	9,52	6,44	3,92	1,50	-0,39	-2,48	-4,97	-7,21	-8,58	-10,06	-11,40	-12,89
EN_NPi2020_500	WITCH 5.0	39,15	39,25	23,42	16,91	10,87	6,96	4,04	1,74	-0,23	-1,13	-1,20	-1,24	-1,27	-1,19	-1,22	-1,25	-1,26	-1,27
EN_NPi2020_500f	WITCH 5.0	39,15	39,25	25,80	20,41	16,32	13,79	10,50	7,33	4,66	2,15	0,21	-1,90	-4,35	-6,33	-8,01	-9,54	-10,89	-12,37
SSP1-19	WITCH-GLOBIOM 3.1	39,15	38,14	24,40	10,71	9,10	7,49	5,28	3,07	1,15	-0,76	-2,30	-3,84	-5,56	-7,27	-8,28	-9,29	-9,49	-9,69
SSP4-19	WITCH-GLOBIOM 3.1	39,15	40,14	26,51	12,94	11,15	9,37	6,77	4,18	1,96	-0,24	-1,93	-3,61	-5,46	-7,30	-8,35	-9,40	-10,12	-10,84
CD-LINKS_NPi2020_1000	WITCH-GLOBIOM 4.4	39,15	41,97	29,26	21,70	18,70	16,15	13,38	10,96	8,19	5,43	3,84	2,25	0,35	-1,54	-3,52	-5,49	-6,76	-8,04
CD-LINKS_NPi2020_400	WITCH-GLOBIOM 4.4	39,15	41,97	26,30	16,29	11,64	8,19	4,84	2,30	-0,07	-2,43	-4,09	-5,75	-8,19	-10,62	-12,52	-14,41	-14,19	-13,96

Note: Corresponding to the following AR6 database variable: AR6 climate diagnostics|Infilled|Emissions|CO2.
Source: Authors and (Byers et al., 2022[20]).

Annex B. Relative stringency of the Paris-consistency criteria

Applying the different Paris-consistency criteria from the criteria framework (Table 3.1) to the IPCC AR6 scenarios database, alone or in combination, results in selecting different sets of scenarios. The intersections and relative stringencies of the criteria are shown in Figure B.1. For example, there are a total of 761 scenarios that reach net zero CO_2 emissions by the end of the century in the AR6 scenarios database. Of those, 266 scenarios only comply with GHG emissions peaking before 2025, without complying with any of the other criteria listed in Figure B.1 (keeping global warming below 2°C with 90% or 78% chance, keeping global warming below 1.5°C in 2100 with 50% chance, avoid a high overshoot of 1.5°C with 50% chance, reaching zero GHG by 2100). The least stringent criterion is the peaking of GHG emissions by 2025. There are indeed 955 scenarios in total that comply with this criterion in the IPCC AR6 scenarios database. Only 6 scenarios comply with another of the listed criteria, without having emissions peak before 2025. The combination of all criteria results in the selection of the stringent Paris-consistent envelope of 26 scenarios (last box on the right).

Figure A B.1. Intersection sizes of sets of scenarios compliant with different Paris-consistency criteria



Source: Authors using data from the AR6 scenarios database (Byers et al., 2022[20]).