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1. Changes with respect to the description of work

No changes to deliverable scope.

2. Dissemination and uptake

This deliverable is public and will be available at ELEVATE's website.

3. Short summary of results (<250 words)

The concept of net-zero targets has gained attention in climate policy since the Paris Agreement called for a balance between anthropogenic emissions and removals in the second half of this century. Accordingly, many countries have set up net-zero targets, but formulated in different ways. In this study, we explore how the different formulations of net-zero on a global scale can shift the exact timing of net-zero, which can also have implications for national net-zero targets. Our analysis is based on the IPCC scenario database and own calculations using a simple integrated assessment model. Our findings indicate that applying different Global Warming Potentials can shift the timing of net-zero CO_2 and greenhouse gas (GHG) emissions by a few decades, both for <1.5°C targets (with and without overshoot) and <2°C targets. The net-zero year also depends on by how much emissions are reduced in the short term: higher 2030 emission levels implies that a faster transition after 2030 is needed, leading to earlier net-zero emissions and more net-negative emissions. Our results indicate the importance of specifying the exact conditions of net-zero targets of countries, especially regarding GWP metrics and which gases are included. Moreover, for achieving 1.5°C with no or small overshoot, immediate rapid emission reductions are more important than achieving net-zero GHGs.

4. Evidence of accomplishment

See report below.

Version log

Version	Date	Released by	Nature of Change
1	23-06-2023	Isabela Tagomori (PBL)	First draft
2	17-07-2023	Isabela Tagomori (PBL)	Revised, based on internal review

Table of contents

List of figures

List of tables

1. Introduction

In recently years, net-zero targets have emerged as a new type of climate policy pledge. They express the year in which a balance between emission sources and emission sinks is first reached (such that the net emissions added to the atmosphere equal zero). The idea arises from the fact that, to stabilise climate change, CO_2 emissions should eventually fall to zero (given the long lifetime of this gas). Zero emissions can be reached by simply eliminating all emissions or by balancing any remaining emissions by carbon removals (Rogelj *et al* 2015, Höhne *et al* 2020, van Soest *et al* 2021b).

Net-zero can be applied on different scales. Net-zero, first of all, makes sense as a concept on a global level (given the physics). With the 2015 Paris Agreement, 197 countries agreed to limit global warming to well below 2°C and pursue efforts to limit it to 1.5°C, as well as reaching net-zero GHG emissions somewhere in the second half of the century (UNFCC 2015). At the same time, many countries, cities, and companies have expressed their climate ambition as a net-zero emissions target (Hale *et al* 2022). While the IPCC Sixth Assessment Report (AR6) discusses a large set of scenarios in relation to temperature goals and net-zero years (IPCC 2022), the question how this is translated to the national level is up to the countries themselves (based on the large differences between them).

The technicalities behind a net-zero target are important, as these can change the timing of net-zero. At the moment, there are many formulations of net-zero which can have significant policy implications, both nationally and internationally. So-far, some studies looked at the conceptual different between net-zero targets (Hale *et al* 2022, Fankhauser *et al* 2022, Levin *et al* n.d., Rogelj *et al* 2021, Loveday *et al* 2022). In this study, we try to provide some more clarity by indicating the consequences of formulating net-zero targets differently on the global scale. Hence, we focus on the technicalities of achieving global net-zero emissions, and how the timing of net-zero changes as the technicalities behind net-zero are defined differently. First, we discuss the considerations behind different net-zero emission targets. Second, we describe the method used in this study to analyse the impact of different considerations of net-zero on the timing of net-zero year. We then present results followed by a discussion, and conclusions.

2. Global net-zero: considerations and formulation

The Paris Agreement has established a temperature goal of staying well-below 2°C and to pursue efforts to stay below 1.5°C. Based on this global climate goal, many countries have declared specific net-zero target years (Figure 1). The year 2050 is by far the most common net-zero year. This is mostly based on the observation in the IPCC assessment report that CO_2 emissions need to reach net-zero around 2050 for reaching 1.5°C with no or limited overshoot.

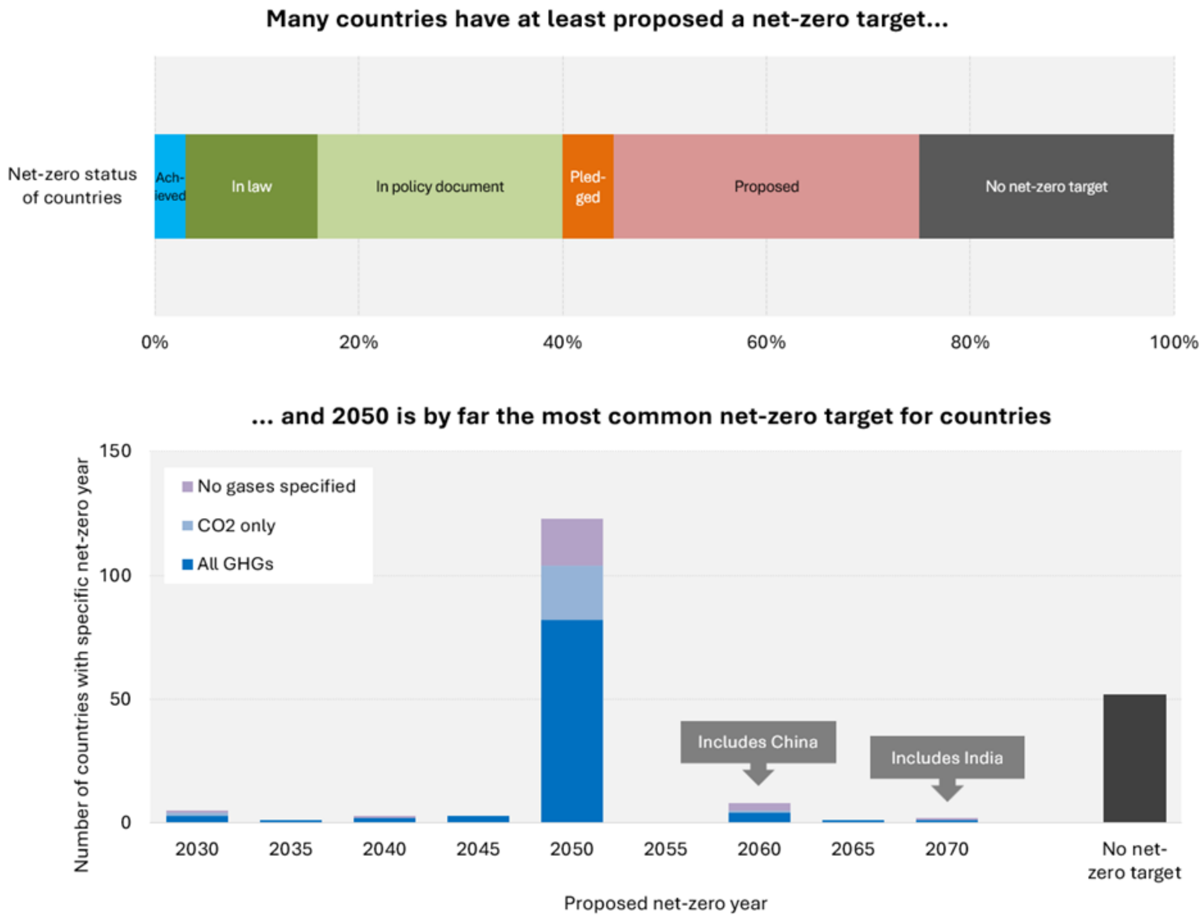

Figure 1 - Overview of net-zero status of countries and proposed net-zero years

Currently, there is no international agreement which describes how a net-zero target should be formulated. This has led countries to construct different formulations of net-zero. While some countries include the full Kyoto set of greenhouse gases, others focus only on CO_2. There are also differences in the reliance on negative emissions. Moreover, some pledges specify the pathway how to reach net-zero while others leave this open. Table 1 lists considerations for a global net-zero target that might shift its timing. Although this study focuses on global net-zero, these results can have implications for net-zero targets on a national level and might be used as guides for constructing national net-zero targets. Therefore, an overview of the different considerations for the formulation of net-zero targets will be addressed in this chapter.

Table 1 - List of considerations for global net-zero that can shift its timing

Considerations for global net-zero that can shift its timing		
Pathway	**Scope**	**Other relevant considerations not part of this study**
• When would net-zero be reached? • What are the interim targets required to reach net-zero in a certain year given a certain emissions budget and (net-) negative emission usage? • To what extent are (net-) negative emissions used?	• What temperature goal does the target contribute to? • Is temperature overshoot allowed? • Is the target focused on net-zero CO_2 or also on other GHGs? • What conversion metric is used for non-CO_2 GHGs?	• Are national greenhouse gas inventories used to count emissions or global models? • What equity and fairness principles should be applied? • Are climate change damages included in determining optimal emission pathways?

2.1. Net-zero, temperature goal, overshoot, and delayed action

The first clear factor that determines the net-zero year is the overall ambition of climate policy. There is a large difference between the net-zero year for scenarios that remain well-below 2°C and those remain below 1.5°C (with no or limited overshoot). Similarly, also overshoot has a major role. Delayed climate action might also have consequences for the timing of net-zero. According to IPCC AR6 (IPCC 2022), most 1.5°C and 2°C scenarios peak emissions around 2020-2025, and then follow a rapid and sustained transition towards net-zero emissions. CO_2 emissions should be reduced by around 45% in 2030 (compared to 2010), to have a likely chance of limiting warming to 1.5°C without overshoot, or around 25% by 2030 (compared to 2010), to have a likely chance at 2°C warming. Following the current NDC pledges, emissions will need to be reduced even faster after 2030 to compensate for the delayed start and to reach 1.5°C or 2°C by 2100.

2.2. Emissions scope: CO_2 vs GHGs

Terminology when referring to net-zero targets is found to be often contradicting. "Carbon neutrality" is usually applied to climate targets referring to net-zero CO_2 and "climate neutrality" to net-zero GHGs, but these different definitions are sometimes mixed up. The emissions scope, i.e., defining weather the net-zero target refers to CO_2 or GHGs, is of utmost importance. A net-zero GHG target is more ambitious than a net-zero CO_2 target for the same year. If a net-zero GHG target is set, net-zero CO_2 should often have been achieved many years earlier (van Soest *et al* 2021b).

From the larger emitters, some focus solely on CO_2 (e.g., China) while others cover all GHGs (e.g., the European Union and the United States). Furthermore, some countries might only report a subset of GHG emissions. For example, when emissions of some gases might be more difficult to measure, or when there might be a gap between reporting and actual emissions (Grassi *et al* 2021). Non-Annex I countries are also not obliged to report F-gas emissions to the UNFCCC (UNFCCC 2023). These factors can create a mismatch between reported GHG emissions and actual emissions, which will influence the timing of net-zero GHGs.

2.3. Long-term (net-) negative emissions

Negative emissions are expected to offset remaining emissions, and potentially help compensate for overshooting a certain carbon budget. Net-negative emissions result from the case where there is more carbon dioxide removal (CDR) than emissions to be offset (Minx *et al* 2018, Fuss *et al* 2018, Prütz *et al* 2023). However, there are many issues involved in relying on them in the future. For example, forestry and land-use-related projects require large amounts of land, and the use of large-scale monoculture plantations can negatively impact biodiversity and might compete with food security and water supply (Fujimori *et al* 2022, Hasegawa *et al* 2020). Costs are also generally high, storage locations need to be relatively close to the point source, and projects might not be socially accepted (Fuss *et al* 2018).

Targets of some countries heavily rely on CDR or international offsets from forestry- and land-use-related CDR to compensate for emissions. Most 1.5°C pathways with and without overshoot also require extensive net-negative emissions alongside emission reductions. Even though IAMs can reach extensive levels of negative emissions, there are currently still many uncertainties and risks, and the availability of such technologies might impact the timing of net-zero.

2.4. Conversion metrics for non-CO_2 GHGs

Conversion metrics are used to add up and compare all greenhouse gases by converting them into CO_2-eq. They can influence net-zero in two ways:

1) A lower value for the conversion metric results in a net-zero GHG closer to net-zero CO_2. A higher value results in a net-zero GHG further from net-zero CO_2 to the extent that net-zero GHG might not be reached at all.

2) Conversion metrics can also influence policy instruments and abatement, such as in the case of a CH_4 price that is dependent on the CO_2 price (Berg *et al* 2015), which is often the case in IAMs. A higher value for the conversion metric will increase the price for a non-CO_2 gas compared to the CO_2 price. Mitigation of this non-CO_2 gas will then be given more priority compared to when conversion metric value is lower. This might influence the timing of net-zero GHG, as well as that of net-zero CO_2.

There are many different types of conversion metrics that have been developed, which all come with benefits and downsides. The most prominently used is the Global Warming Potential (GWP), which integrates the radiative forcing of a certain gas over a chosen time horizon relative to that of CO_2. The GWP is defined as the ratio of the time-integrated radiative forcing from the release of 1 kg of a gas compared to 1 kg of CO_2 (Equation 1). The larger the GWP, the more a certain gas warms the Earth compared to CO_2 over that time horizon.

Equation 1. Calculation of the global warming potential (GWP) of gas "i" over time horizon "H":

$$GWP_i(H) = \frac{\int_0^H RF_i(t)dt}{\int_0^H RF_{CO_2}(t)dt}$$

i: greenhouse gas

t: time

H: time horizon over which GWP is determined

RF: radiative forcing from emission of 1 kg of gas at t=0

The chosen time horizon has a large influence on the GWP value. A gas which has a large radiative forcing effect but has an atmospheric lifetime of years to decades will have a large warming effect when it lingers in the atmosphere, but this warming effect will cease once it has disappeared. Still, due to the way it is calculated, the GWP will smear out the total warming effect of that gas across the chosen time horizon, up to long after the actual warming effect of that gas might have disappeared.

The time horizons proposed by the IPCC's First Assessment Report are currently still used. These are the GWP over 20 years, (GWP-20), over 100 years (GWP-100) and over 500 years (GWP-500). The GWP values (GWP-20, GWP-100 and GWP-500) according to IPCC AR6 are presented in Table 2.

Table 2 - GWP values for GWP-20, GWP-100 and GWP-500 from AR6

GWP values over for GWP-20, GWP-100 and GWP-500 from AR6			
	GWP-20	GWP-100	GWP-500
CO_2	1	1	1
non-fossil CH_4	79.7 ± 25.8	27.0 ± 11	7.2 ± 3.8
fossil CH_4	82.5 ± 25.8	29.8 ± 11	10.0 ± 3.8
N_2O	273 ± 118	273 ± 130	130 ± 64

There are trade-offs involved in choosing one timeframe over another. A short timeframe will put more weight on short-lived greenhouse gases, therefore giving short-term climate effects of short-lived gases more emphasis compared to the long-term effects of CO_2. Emphasizing mitigation of short-lived greenhouse gases, such as CH_4, can be important to reduce warming in the short term and buy more time for CO_2 mitigation, as proposed by some studies (Fesenfeld *et al* 2018, Ocko *et al* 2017). On the other hand, when using a time horizon of 500 years, short lived greenhouse gases are given less weight compared to CO_2, which might help to mitigate climate effects on longer timescales such as long-term warming and ocean acidification.

GWP-100 is a compromise for these trade-offs, but therefore prioritizes neither short-term nor long-term effects of certain greenhouse gases (Shine 2009). But there are consequences of using GWP-100 for net-zero targets. Applying GWP-100 to a global net-zero GHG target will not result in temperature stabilization, but in a constant temperature decline. This is because to reach net-zero GHG, carbon dioxide removal is used to balance other, shorter-lived non-CO_2 gases. When short-lived gases are converted to CO_2-eq using GWP-100, they would in theory be in the atmosphere for 100 years, when, in reality, they will disappear after years or decades.

Next to changing as a function of the time horizon, the GWP also changes depending on the IPCC assessment report one chooses. Countries that are part of the Paris Agreement agreed to use GWP-100 in their reporting. However, in reporting their NDCs to the UNFCCC, 31% of countries used GWP-100 values from the Fifth Assessment Report (AR5), 17% of the Forth Assessment Report (AR4), and 16% from the Second Assessment Report (SAR). Moreover, 35% of countries did not provide information on the metric they used.

To overcome some of the shortcomings of the GWPs, alternative pulse-based metrics have been proposed recently (Allen *et al* 2018, Collins *et al* 2020). These try to overcome the issue of the horizon dependency of GWPs by equating an increase in the emission rate with a pulse emission of CO_2-warming equivalents (CO-$_2$-we). These pulse-based metrics are called CGTP (combined global temperature change potential) and GWP*. Combining cumulative emissions of some non-CO_2 gas with GWP* or CGTP and multiplying this with Transient Climate Response to Emissions (TCRE; the link between cumulative CO_2 and temperature) gives a much better estimate of the warming effect caused by the emission of the non-CO_2 gas compared to using other GWP variants. For a short-lived non-CO_2 greenhouse gas such as CH_4, using a pulse-based conversion metric means that stabilizing emissions over a decade or two is sufficient to reach zero CH_4 emissions in terms of CO_2-we. Reducing emissions over a decade or two would in fact create negative CO_2-we emissions. While these pulse-metrics can be applied as microclimate model (MCM) because of their near-linear relationship with temperature, there are many issues in applying it as metric for policy instruments (Meinshausen and Nicholls 2022).

2.5. Downscaling net-zero targets to the national level

Net-zero targets are not only applied at the global level but also at national and corporate levels. However, there is currently no established method for achieving net-zero emissions. One approach is to use the regional and sectoral information in the global scenarios to determine the years in which regions and sectors achieve net-zero emissions. This would be consistent with cost-efficient allocation. However, it is important to note that cost-optimal allocation does not necessarily guarantee fairness. In fact, these scenarios often result in higher costs per unit of GDP for low-income countries due to their higher carbon intensity and greater potential for emissions reduction. To address fairness, factors such as equity, historical responsibility, and capability can be considered. Previous publications have explored the derivation of national emission reduction targets or carbon budgets using these concepts, which can also inform net-zero years. It is worth noting that there is no established definition of what constitutes a fair allocation, leading to a wide range of results in these studies. Nevertheless, fairness considerations can be observed in the net-zero targets set by different governments. For instance, the EU argues that its net-zero greenhouse gas target for 2050 is more ambitious than the global net-zero CO_2 target consistent with staying below 1.5°C with limited or no overshoot, thus demonstrating its commitment to doing more than the global average. Similarly, India and China indicate that their net-zero targets, set for years later than 2050, are driven by their development needs.

3. Methods

In this study, we use the results of Integrated Assessment Models (IAMs) to perform a sensitivity analysis for the net-zero targets, where the timing of net-zero is analysed for different formulations of components of global net-zero: i) global temperature, ii) emissions scope, iii) 2030 emissions level, iv) cumulative negative emissions, and v) GWP metric. For the GWP metric, we perform both an ex-post and ex-ante analysis. The analysis used the model runs collected in the AR6 Database (Byers *et al* 2022). The AR6 Database, along with metadata for each scenario, is hosted online by the International Institute for Applied Systems Analysis (IIASA)[1]. For this study, the data was processed using Python. In the ex-ante analysis for the GWP-metric new scenarios are developed with different conversion metrics. For this, we extended and applied the simple integrated assessment model MIMOSA (van der Wijst *et al* 2021).

3.1. Pre-processing the AR6 Database

3.1.1. Selection of scenarios from the AR6 Database

The more than 2000 global scenarios included in the database allow for extensive ex-post analysis of different scenarios to find relations within results. In this study, we only use a subset of the available scenarios. First of all, we follow the vetting criteria also used by IPCC. Second, this study considers only the outcomes of categories <1.5°C-L, <1.5°C-H, and <2°C runs since these scenarios are in line with the Paris Agreement. Note that in AR6 these categories are referred to as C1, C2, and C3, respectively, but are here renamed to provide for clarity (Table 3). In total 541 scenarios passed the historical vetting and fall within these categories.

Table 3 - Warming categories used in this study

IPCC AR6 GWL category name	GWL label	Description	Warming category name in this study and color
C1	Limit warming to **1.5°C** (>50%) with **no or limited overshoot**	Reach or exceed 1.5°C during the 21st century with a likelihood of ≤67%, and limit warming to 1.5°C in 2100 with a likelihood >50%. Limited overshoot refers to exceeding 1.5°C by up to about 0.1°C and for up to several decades.	**<1.5°C-L**

[1] Available at: https://data.ece.iiasa.ac.at/ar6//#/downloads.

C2	Return warming to **1.5°C** (>50%) after a **high overshoot**	Exceed warming of 1.5°C during the 21st century with a likelihood of >67%, and limit warming to 1.5°C in 2100 with a likelihood of >50%. High overshoot refers to temporarily exceeding 1.5°C global warming by 0.1°C–0.3°C for up to several decades	**<1.5°C-H**
C3	Limit warming to **2°C** (>67%)	Limit peak warming to 2°C throughout the 21st century with a likelihood of >67%	**<2°C**

3.1.2. Calculating the net-zero year

We calculate the net-zero year of scenarios based on the emissions from MAGICC[2] (Model for the Assessment of Greenhouse Gas Induced Climate Change) for each scenario. For the net-zero year, we use the first year in which emissions are reported below zero. This approach is slightly different compared to the method applied by the IPCC, where scenarios are sometimes marked as having reached net-zero even though MAGICC emissions are still positive. This is caused by the different climate models that are used for the individual IAMs compared to the MAGICC model that is run for every single scenario in the AR6 Database. In case MAGICC does not report zero or negative emissions but the scenario's own climate model does, then the net-zero year of the scenario's own model is used. This is often the case for scenarios that stabilize emissions at low levels (<1 Gt/yr). In this study, however, we only calculate net-zero based on MAGICC emissions. This means that the net-zero years calculated here will differ slightly from those calculated by the IPCC.

The scenarios in the AR6 Database only run until the year 2100. There are various scenarios that do not reach net-zero before this time. Leaving these scenarios out would give a distorted image. To overcome this issue, all scenarios that do not reach net-zero are replaced with some net-zero year after 2100, in this case 2110. This is a similar method to the one used by the IPCC in AR6.

For this study, we focus on both net-zero CO_2 and net-zero GHG scopes. Unless specifically stated otherwise, we use the GWP-100 value from AR5 for summing emissions in terms of CO_2-eq, since this is currently the most used metric by countries. For F-gases, however, we use the GWP-100 value from AR6, given that F-gases emissions from MAGICC reported in the AR6 Database have already been converted to CO_2-eq using GWPs from AR6 and have all been summed. Since GWPs

[2] More info about MAGICC at: https://magicc.org

from AR6 are relatively similar to AR5 and F-gas emissions are not a large contributor to total CO_2-eq emissions, we accept this as a small shortcoming.

3.2. Ex-post analysis of the scenarios

After selecting the scenarios from the AR6 Database, we plot the timing of net-zero for each scenario within its warming category. Then we change each parameter at a time, for example the emission scope, and recalculate the timing of net-zero for each scenario. This allows for a general comparison between the timing of net-zero when it is formulated differently. A schematic overview of the analysis method is presented in Figure 2.

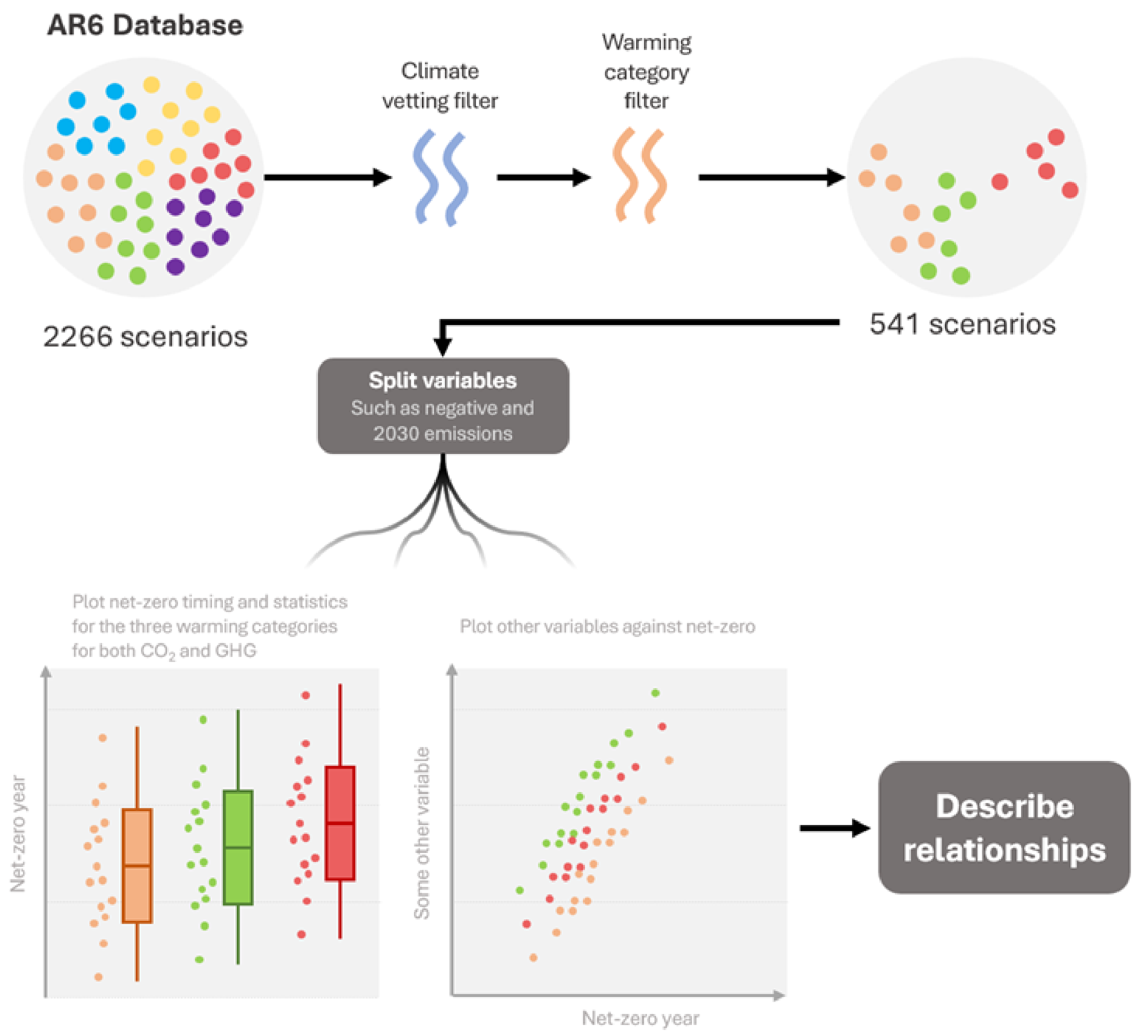

Figure 2 - Method for the analysis of the selected scenarios (from the AR6 Database)

3.2.1. Warming categories

To find the relationship between net-zero and warming, we first look at the different warming categories. These have been categorized based on their 2100 temperatures and potential overshoot. The categories, however, are based on ranges which can vary up to 0.5°C. The <1.5°C-L and <1.5°C-H categories contains scenarios between 1°C-1.5°C warming, and the <2°C category contain scenarios between 1.5°C-1.8°C warming. Only focusing on distinct warming categories will not show the entire picture. We therefore also want to look specifically into the exact 2100 warming for each scenario. Climate diagnostics for all scenarios are provided from MAGICC. Here, we take the surface air temperature 50th percentile since this is the most probable surface air temperature.

3.2.2. Emissions scope

The AR6 Database contains climate diagnostics for individual emissions of CO_2, CH_4, N_2O, and F-gases. This allows recalculation of the timing of net-zero when considering different gases. We also analyse the effect of including a smaller subset of GHGs (for example only CO_2+CH_4) for the timing of net-zero GHG.

3.3.3. 2030 emissions

The AR6 Database contains yearly emission data. This allows us to split scenarios by some cut-off value for emissions in 2030. In this case, we select this cut-off manually at 35 Gt CO_2/yr in 2030. This corresponds to scenarios in the <1.5°C-L category where emissions do not decrease, or only decrease slightly in 2030 compared to 2015. We apply a similar method for GHG emissions, where we use a cut-off value for emissions in 2030 at 46 Gt CO_2-eq/yr. We can then compare the timing of net-zero for scenarios with a delayed start and those without delayed start. We also directly compare the 2030 emission level with the timing of net-zero.

3.3.4. Net-negative emissions

The net-negative emissions are the remaining emissions minus the total negative emissions. In this case, we look at cumulative net-negative emissions. We investigate the relationship of cumulative net-negative emissions and net-zero by plotting them directly against each other.

3.3.5. GWP metrics

We investigate the different ways the GWP values can impact the timing of net-zero. First, we look at the effect of using different time horizons. Specifically, we look into GWP-20, GWP-100, and GWP-500. We use the AR5 values for these GWPs, since AR5 is currently the most used data source for GWP values. Second, we look at different GWP-100 values from different reports. Specifically, we apply GWP-100 from SAR, which has the lowest value and is still used by some countries, AR5, which is currently the most used, and AR6, which is the most recent value. Note that this method of changing the GWP only changes the way net-zero GHG is measured *ex-post*.

3.3. Ex-ante analysis of the impacts of different net-zero formulations

To find out how the GWP can influence mitigation through a non-CO_2 price, we run MIMOSA, which optimizes carbon price paths under assumptions for climate damages, temperature goals, mitigation costs, TCRE, discount rates, and socio-economic developments (van der Wijst *et al* 2021).

3.3.1. New components added to MIMOSA

For this study, we add two new components to the existing MIMOSA model, to incorporate CH_4:

1) CH_4 emissions and abatement. By default, the model runs on CO_2 only. Currently, CH_4 mitigation is included in the CO_2 MAC (Marginal Abatement Cost) curve. Because we are interested in the effect of the GWP in relation to the CH_4 price, we add CH_4 emissions into the model. We first added CH_4 baseline emissions using baseline SSP1-SSP5 scenarios from IMAGE (van Vuuren *et al* 2015). The baseline emissions can be found in the AR6 Database. We also fit a MAC curve equation to an existing CH_4 MAC dataset (Harmsen *et al* 2019). An example of a fitted MAC curve can be found in Appendix I. The MAC curve abatement costs are in \$/t CH_4, such that different GWPs can be applied to convert the CO_2 price into a CH_4 price. The CH_4 abatement costs were then linked to the economic model, such that mitigation costs would be subtracted from the GDP.

2) GWP* as simple climate model. Currently, the model uses a simple conversion of cumulative CO_2 emissions multiplied by the TCRE. The TCRE assumes a certain amount of non-CO_2 emissions, so the only input is CO_2. To still use the TCRE for both CO_2 and CH_4 emissions, we use GWP*. Although GWP* was originally proposed as new GWP variant, it has been shown that cumulative emissions calculated using GWP* can function as a simple climate model to calculate temperature together with cumulative CO_2 emissions and the TCRE (Allen *et al* 2018, Cain *et al* 2019, Lynch *et al* 2020, Meinshausen and Nicholls 2022). CH_4 emissions converted with GWP* function as a correction factor for the TCRE. Although this simple climate model is far less complex compared to a model such as MAGICC, it does provide an improvement in MIMOSA compared to when only a CO_2-TCRE relationship was used. To use GWP* in the TCRE, cumulative emissions should be used as input in the calculation. The output will then be in cumulative CO_2-we. To calculate GWP*, we use the equation:

$$E_{cum}^{*}\ (t) = GWP_H * \left[g * \frac{E_{cum,t-\Delta t} - E_{cum,t}}{\Delta t} * H + s * E_{cum,t}\right]$$

E_{cum}^{*}: cumulative emissions of a gas expressed in CO_2-we at time "t"

H: time horizon for the GWP values

GWP_H: the GWP value for a gas the over time horizon "H"

g: coefficient for the emission rate contribution (1.13 is recommended)

Δt: time over which the emission pulse in spread out (20 years is recommended)

$E_{cum,t-\Delta t}$: cumulative emissions in mass of a gas at year "t-Δt"

$E_{cum,t}$: cumulative emissions in mass of a gas at year "t"

s: coefficient for the emission stock contribution (0.25 is recommended)

Note: recommended values from (Cain *et al* 2019)

The output of the GWP* equation can be added up to cumulative CO_2 emissions and then multiplied by the TCRE to find the temperature. Since we run MIMOSA only from 2020 onwards and since the GWP* calculation requires historical emissions, we used historical CH_4 emissions from IMAGE. Figure 3 shows a schematic representation of how MIMOSA was used for this study.

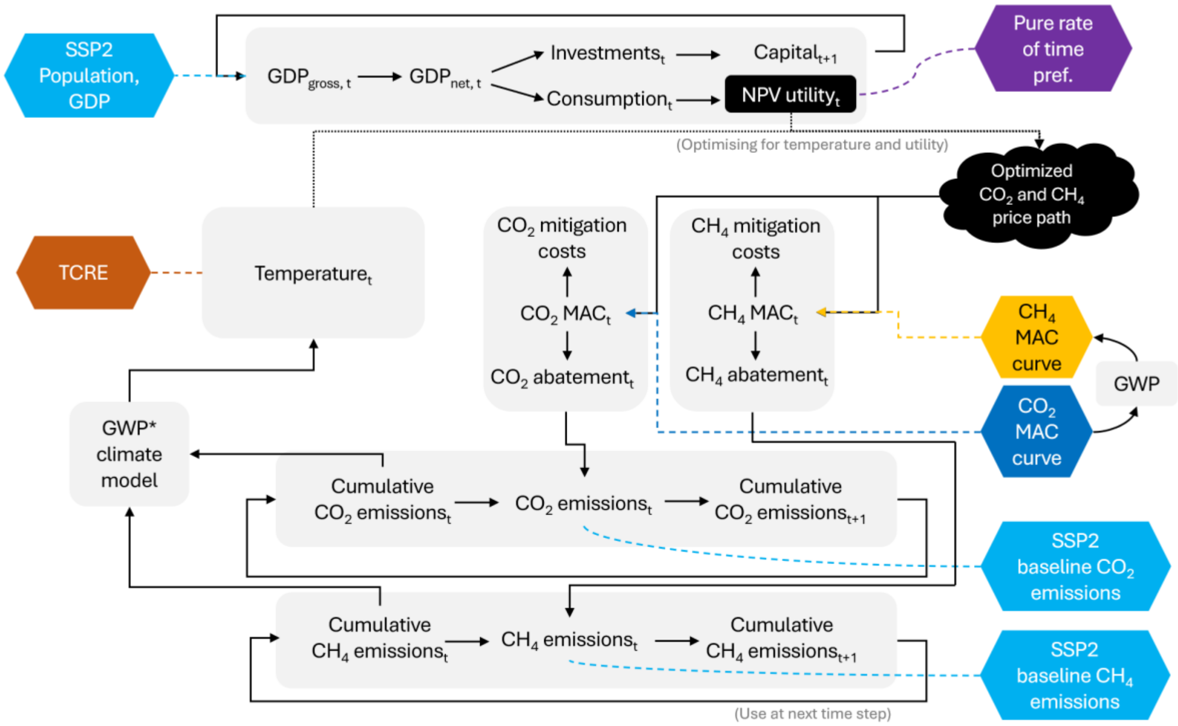

Figure 3 - Schematic representation of MIMOSA and the CH_4 components added

3.3.2. MIMOSA model runs

To make MIMOSA as similar as possible to other IAMs used for the IPCC assessments, some of the default parameters of the model were adjusted.

- SSP2 inputs;
- No climate damages and costs;
- No emission trade;
- No baseline CO_2 intensity (baseline emissions from IMAGE);
- Inequality aversion was set to zero;
- Net-negative emissions were set to a maximum of -10 $GtCO_2$/yr;
- No carbon budget limit (constraint set for 2100 temperature).

A total of 6 scenarios were run. These 6 scenarios consist of combinations of two different 2100 temperatures and four different GWPs. We run scenarios for both 1.5°C and 1.8°C warming by 2100, and for GWP-20, GWP-100, and GWP-500 from AR5. We have chosen these specific temperatures because they roughly correspond with the Paris Agreement limits of 1.5°C and well-below 2°C. As for the GWPs, we chose specifically these GWPs to find the differences between GWPs with different time horizons.

4. Results

4.1. Net-zero and warming categories

Net-zero CO_2 emissions

The timing of net-zero CO_2 shifts considerably between warming categories. Higher warming generally implies later net-zero CO_2 years (Figure 4).

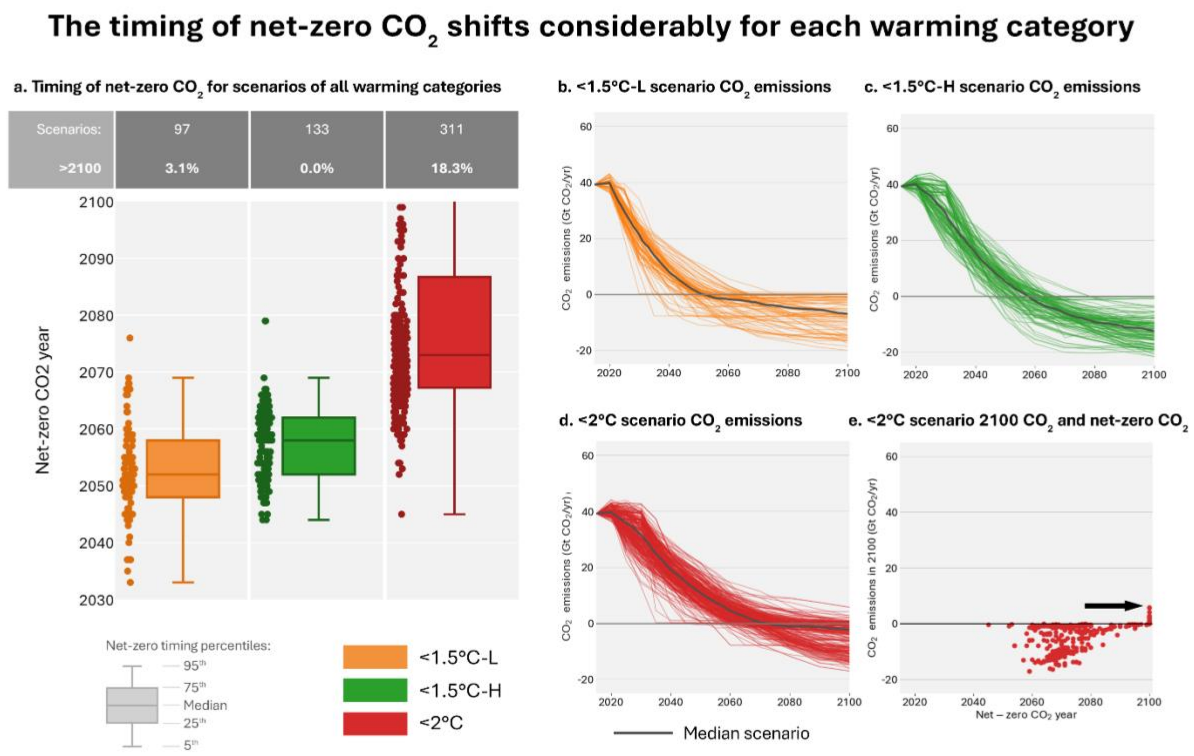

Figure 4 - Timing of net-zero CO_2 and CO_2 emission pathways for three warming categories

For <1.5°C-L scenarios, a strategy of immediate, rapid, and sustained CO_2 mitigation early in the century is required to prevent overshoot of the 1.5°C target. This, however, allows for some flexibility in the timing of net-zero CO_2, causing the net-zero CO_2 window to be wide, including some early but also late scenarios (early-2030s to mid-2070s, median 2053). Panel "b" shows how many scenarios slow down the pace of the transition slightly after an immediate and rapid start. In fact, a few scenarios do not reach net-zero CO_2 just hoover above the net-zero line. These scenarios stabilize CO_2 emissions around the middle of the century at very low levels (<1 $GtCO_2$/yr).

<1.5°C-H scenarios all reach net-zero CO_2 after slower mitigation pace up to 2030 which is then compensated for by extensive net-negative emissions. This results in a

net-zero CO_2 window that is narrower – and starts mid-2040s to late-2070s (median 2058). The delayed start and/or slower mitigation pace causes temperature overshoot which requires extensive net-negative emissions. This limits flexibility in the timing of net-zero CO_2.

Almost one-fifth of <2°C scenarios do not reach net-zero CO_2, caused by a delayed start and/or slow mitigation pace, resulting in a late and very wide net-zero CO_2 window (mid-2040s to late-2090s, median 2070). The delayed start and/or slow mitigation pace and absence of extensive net-negative emissions create higher CO_2 emissions and higher 2100 temperature. Scenarios that do not reach stabilize CO_2 emissions at a relatively low level close to net-zero emissions (panel "e").

Net-zero GHG emissions

Our findings indicate that the timing of net-zero GHG can shift considerably between warming category, but that there is substantial spread within all warming categories. Net-zero GHG is most important for <1.5°C-H scenarios. The Paris Agreement calls for net-zero GHG emissions in the second half of the century. Here we show that reaching net-zero GHG is not always necessary to limit warming to the goal in the Paris Agreement (Figure 5).

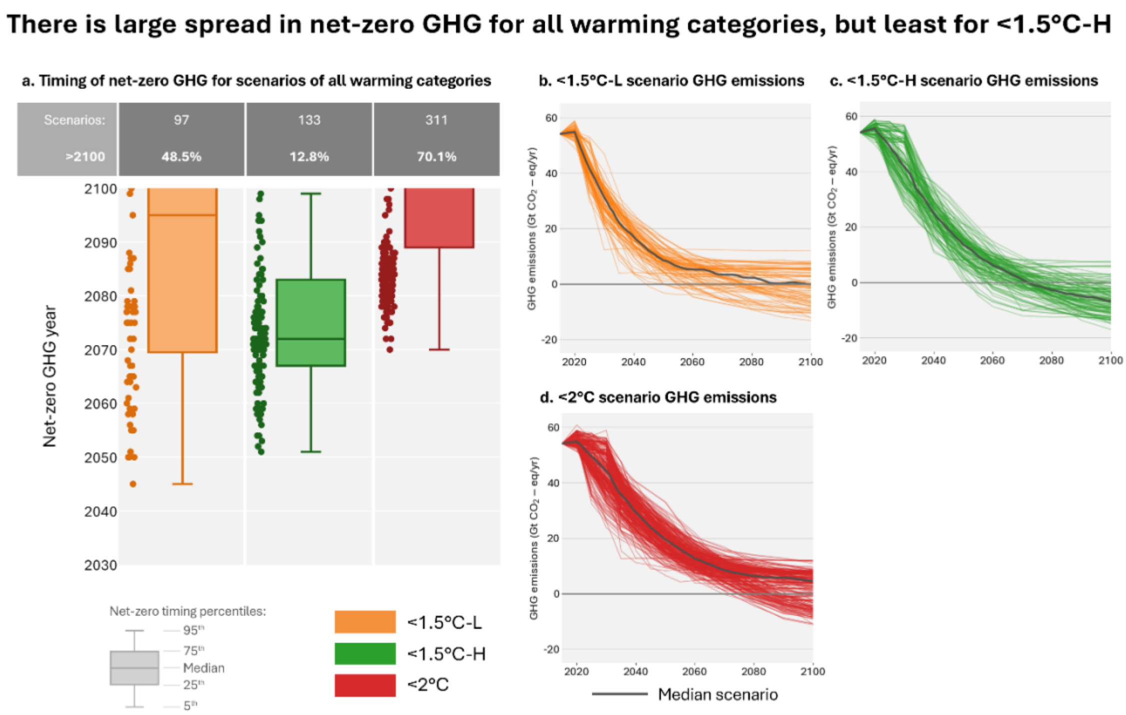

Figure 5 - Timing of net-zero GHG and GHG emission pathways for three warming categories

Similarly as for CO_2, the immediate and rapid mitigation needed to avoid overshoot means for the <1.5°C-L scenarios that the reduction can be slower after the peak temperature. As a result, almost half of these scenarios do not require net-zero GHGs before 2100. However, other scenarios in this category already reach net-zero GHG soon, creating a very wide net-zero GHG window (early 2050s to >2100, median 2095). Scenarios that do not reach net-zero GHG instead stabilize GHG emissions at low levels (panel "b"). Scenarios that do reach net-zero GHG have extensive net-negative emissions, which will result in a strong temperature decline.

For <1.5°C-H scenarios, the temperature overshoot requires such extensive negative emissions that both CO_2 and non-CO_2 emissions are offset and net-zero GHG is reached in the vast majority of scenarios, albeit in a relatively wide window (early 2050s to >2100, median 2072). Scenarios that do not reach net-zero GHG instead stabilize their emissions at a low level close to net-zero GHG.

Because of a delayed start and/or even slower mitigation, some <2°C scenarios only reach net-zero late this century and over two thirds of do not reach net-zero GHG before 2100 (late-2060s to >2100, median >2100). Scenarios without net-zero GHG stabilize emissions at a low level.

Net-zero GHG is more important for <1.5°C-H scenarios compared to <1.5°C-L and <2°C scenarios. The timing of net-zero GHG can shift considerably by warming category, but there is substantial spread and for all warming categories. In only around half of <1.5°C-L and <2°C scenarios reaching net-zero GHG is required. This means that net-zero GHG is not always required for reaching the temperature goals of the Paris Agreement. For <1.5°C-L scenarios, immediate rapid emission reductions are more important than achieving net-zero GHGs.

Correlation between net-zero emissions and warming

Warming is correlated with net-zero CO_2 and net-zero GHG. The correlation is cloudier for <1.5°-L, which is caused by the flexibility these scenarios have to go to net-zero after their early and rapid mitigation. For <1.5°C-H and <2°C scenarios the correlation evolves close to linearly for most scenarios up to around 1.8°C. It shows that the earlier net-zero CO_2 and net-zero GHG is reached, the lower the 2100 temperature generally is. For <2°C scenarios, however, this is not always the case as some scenarios never reach net-zero CO_2 or net-zero GHG, but still limit warming to the goals of the Paris Agreement. It also shows that there can be large differences within one warming category, which can create spread for this results in this study.

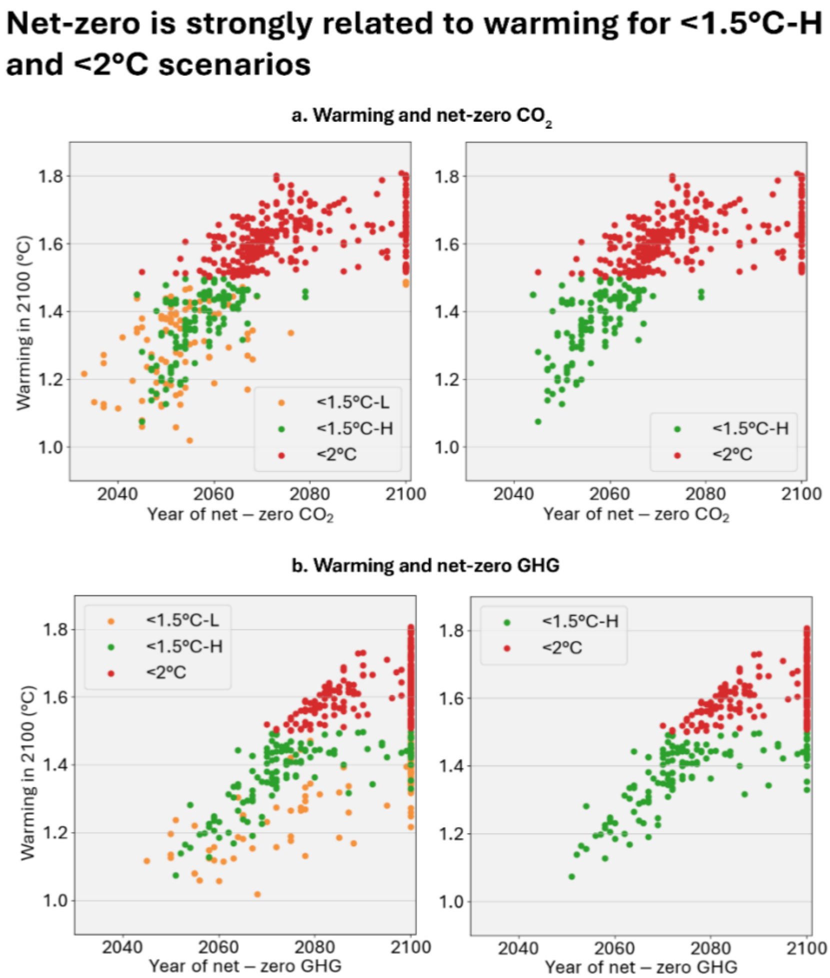

Figure 6 - Net-zero CO_2 year as a function of global surface air temperature (GSAT) by 2100

a) Left: for warming categories <1.5°C-L, <1.5°C-H, and <2°C; b) Right: for warming categories <1.5°C-H, and <2°C only.

4.2. Net-zero and emissions scope

4.2.1. Differences between net-zero CO2 and net-zero GHG

Some countries have defined a net-zero CO_2 goal, but many other countries have defined a net-zero GHG goal. Here we show that the difference in timing between net-zero CO_2 and net-zero GHG is often multiple decades.

Figure 7 demonstrates how the median difference between the timing of net-zero CO_2 and net-zero GHG is multiple decades for the three warming categories. The difference is largest for <1.5°C-L scenarios, caused by the many scenarios that first reach net-zero CO_2 but only reach net-zero GHG late or never at all. For <1.5°C-H scenarios the difference between net-zero CO_2 and net-zero GHG is smallest, caused by the more rapid transition and more extensive negative emissions required after overshooting temperature. For <2°C scenarios, the difference is multiple decades caused by the many scenarios that never reach net-zero GHG this century.

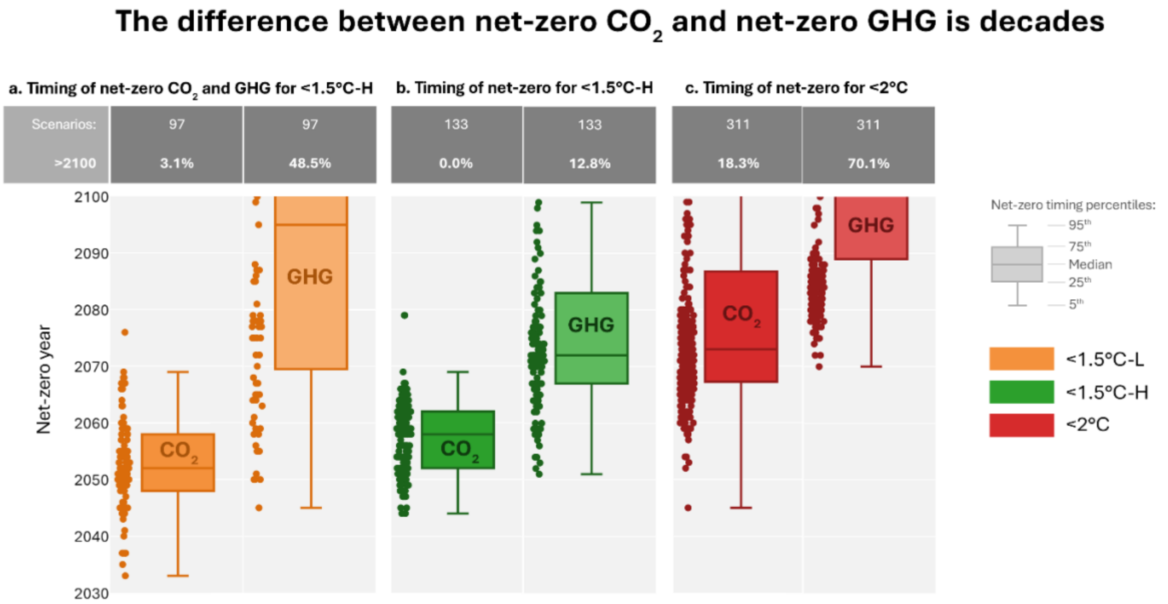

Figure 7 - Net-zero CO_2 compared to net-zero GHG for <1.5°C-L (orange), <1.5C-OS (green), and <2°C scenarios (red)

4.2.2. The contribution of each gas to net-zero GHG

The differences between the CO_2 and GHG net-zero year can be analysed for different gases, showing the influence of CH_4 and N_2O. Including F-gases does not make a large difference. Figure 8 shows how the timing of net-zero GHG shifts as the GHG scope is expanded. For <1.5°C-H, considering CO_2 and CH_4 shifts the net-zero year around a decade compared to CO_2 only. For the other two warming categories the difference is multiple decades, while also introducing considerable additional spread in the timing of net-zero. Considering CO_2, CH_4, and N_2O shifts the net-zero year another few years and adds additional spread. In contrast, the impact of considering F-gases on top of other GHGs is negligible for the timing of net-zero and does not introduce significant extra spread.

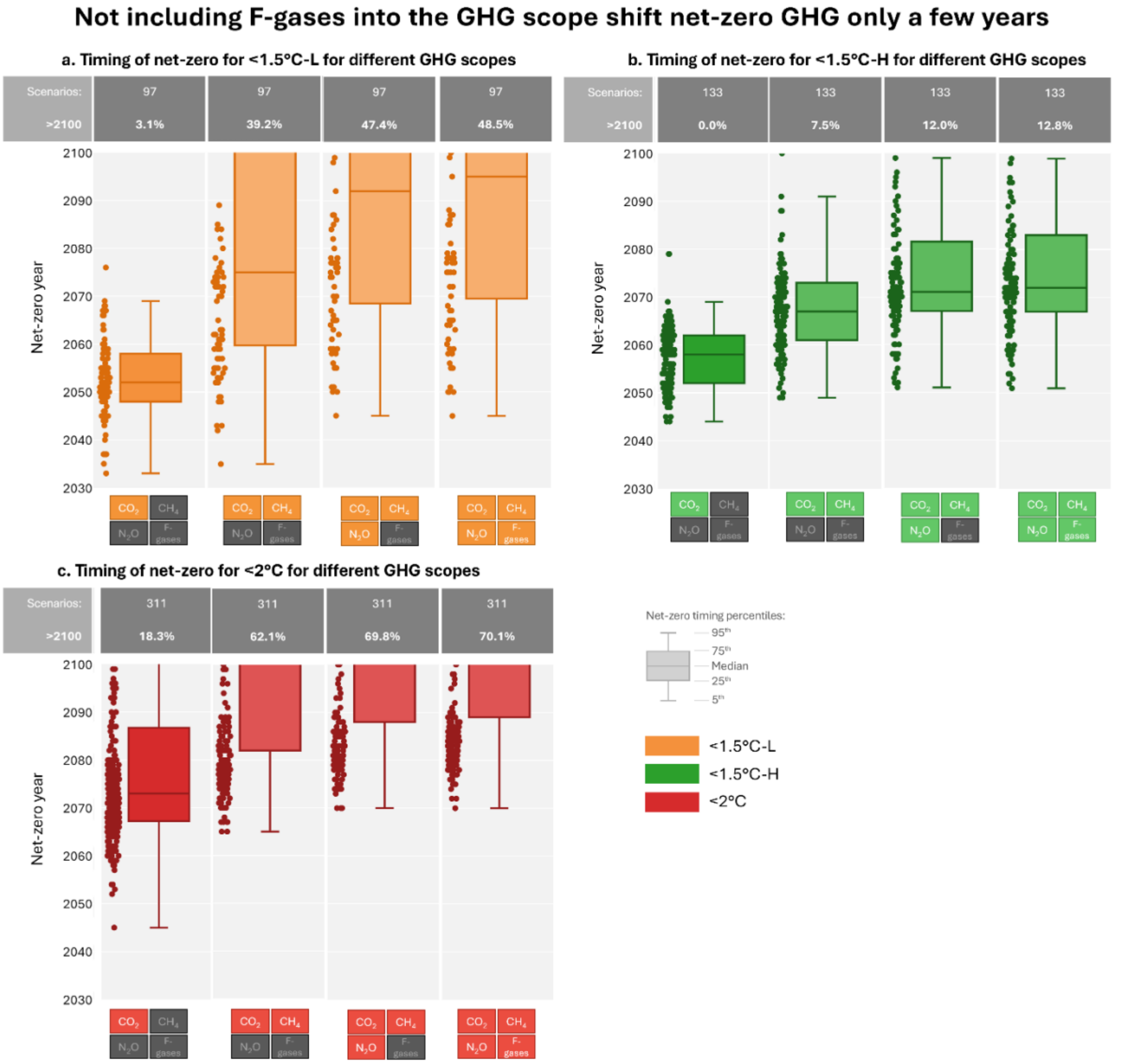

Figure 8 - Net-zero for three warming categories when including different GHGs

a) <1.5°C-L (top; in orange); b) <1.5°C (middle; in green); and c) <2°C scenarios (bottom; in red)

4.3. Net-zero and 2030 emissions

4.3.1. Net-zero CO_2 and 2030 emissions

If emissions are reduced slower (according to the NDCs) this impacts the net-zero year. Interestingly, the impact on net-zero CO_2 <1.5°C-H scenarios is relatively small but there is an impact up to a decade for <2°C scenarios (Figure 9). For <1.5°C-H scenarios, extensive net-negative emissions and/or slightly more rapid transition after 2030 can compensate for high 2030 emissions without requiring a much earlier net-zero CO_2. This is different for some <2°C scenarios, where net-zero CO_2 is earlier when 2030 emissions are high. These scenarios tend to have extensive net-negative emissions or rapid transition towards (near) net-zero after 2030.

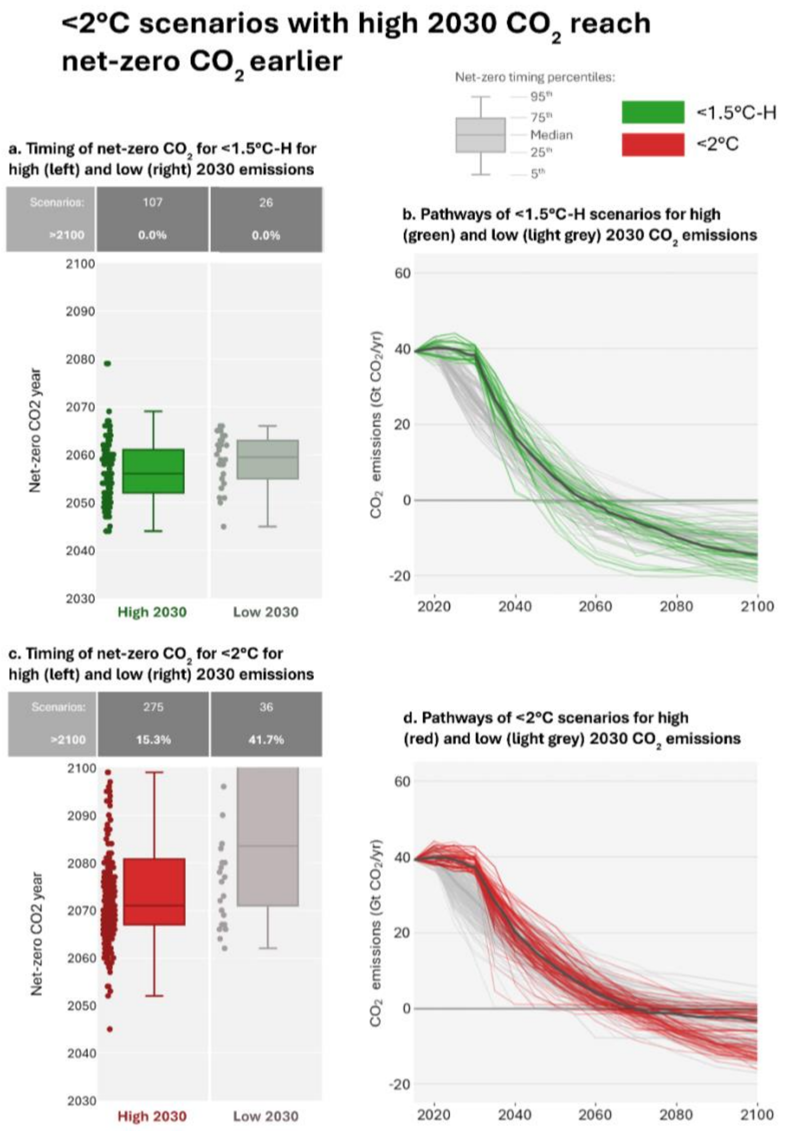

Figure 9 - Timing of net-zero CO_2 and CO_2 emission pathways for scenarios with high (>35 $GtCO_2$/yr; in color) 2030 emissions or low (<35 $GtCO_2$/yr; in grey)

Panels "b" and "d" show the CO_2 emission pathways of delayed action scenarios (in colour). The delayed emission scenarios have a slightly earlier net-zero CO_2 for <1.5°C-H. A faster transition towards net-zero after a delayed start and/or more negative emissions can negate the delayed start. This shows that a delayed onset of CO_2 mitigation does not always create a large difference in the timing of net-zero, as long as the transition is fast enough, and CO_2 removal is deployed such that the carbon budget is adhered to.

This is different for <2°C scenarios. For high 2030 emission scenarios, net-zero CO_2 is reached in more scenarios and earlier. These scenarios start the transition to net-zero quickly after 2030 and sometimes require extensive net-negative emissions.

4.3.2. Net-zero GHG and 2030 emissions

Scenarios with high 2030 GHG emissions reach net-zero GHG more often. This is caused by the higher cumulative emissions in the beginning of the century which are compensated for by negative emissions. These negative emissions are so high that all non-CO_2 emissions are compensated and net-zero GHG is reached. Reaching net-zero GHG therefore becomes more important after high 2030 emissions.

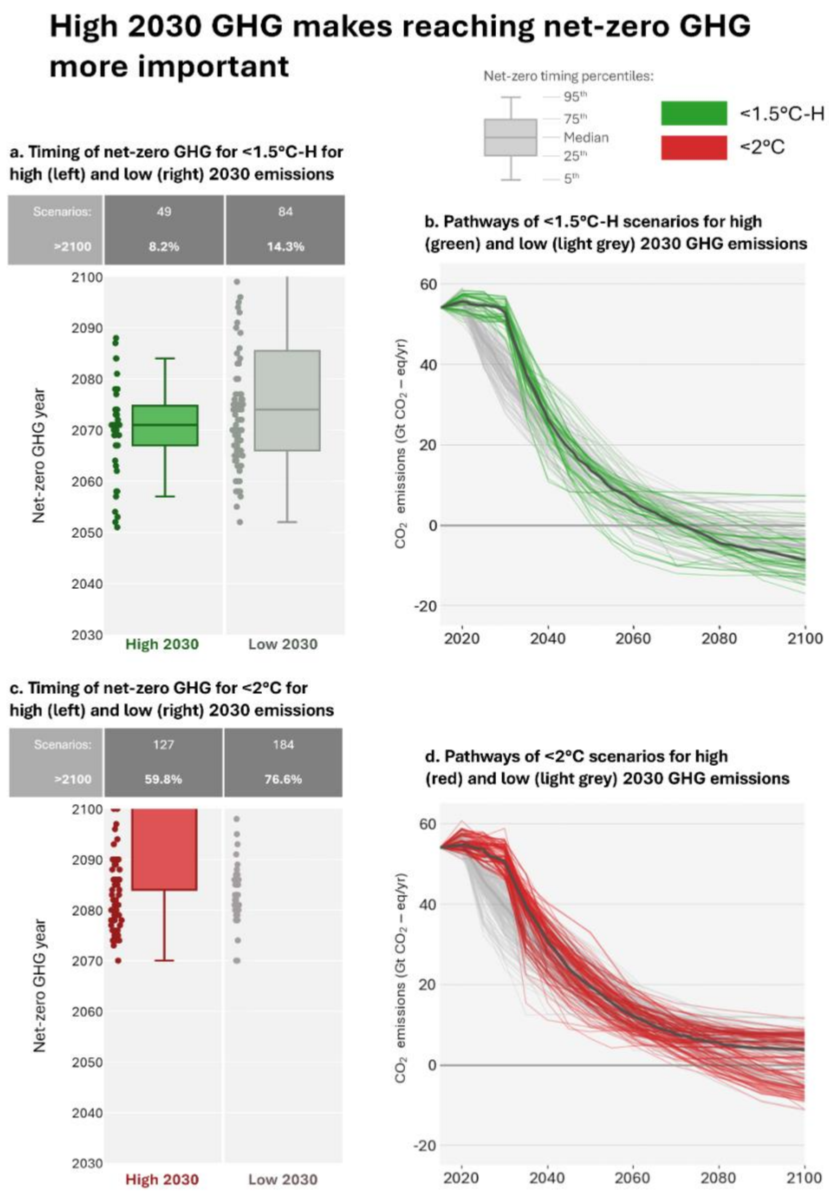

Figure 10 - Timing of net-zero GHG and GHG emission pathways for scenarios with high (>46 $GtCO_2$-eq/yr; in color) 2030 emissions or low (<46 $GtCO_2$-eq/yr; in grey).

4.3.3. The relationship between net-zero and 2030 emissions

Net-zero and 2030 emissions together can indicate which warming category a scenario is on track to reach. Even though the relation between 2030 emissions and net-zero is cloudy, the three warming categories are separated (Figure 11). If a scenario has high 2030 emissions but an early net-zero CO_2 and GHG, it will end up around 1.5°C after an overshoot. If a scenario has low 2030 emissions and early net-zero CO_2, it will end up around 1.5°C. If 2030 emissions are high and net-zero CO_2 and GHG are late, it will reach around <2°C in 2100.

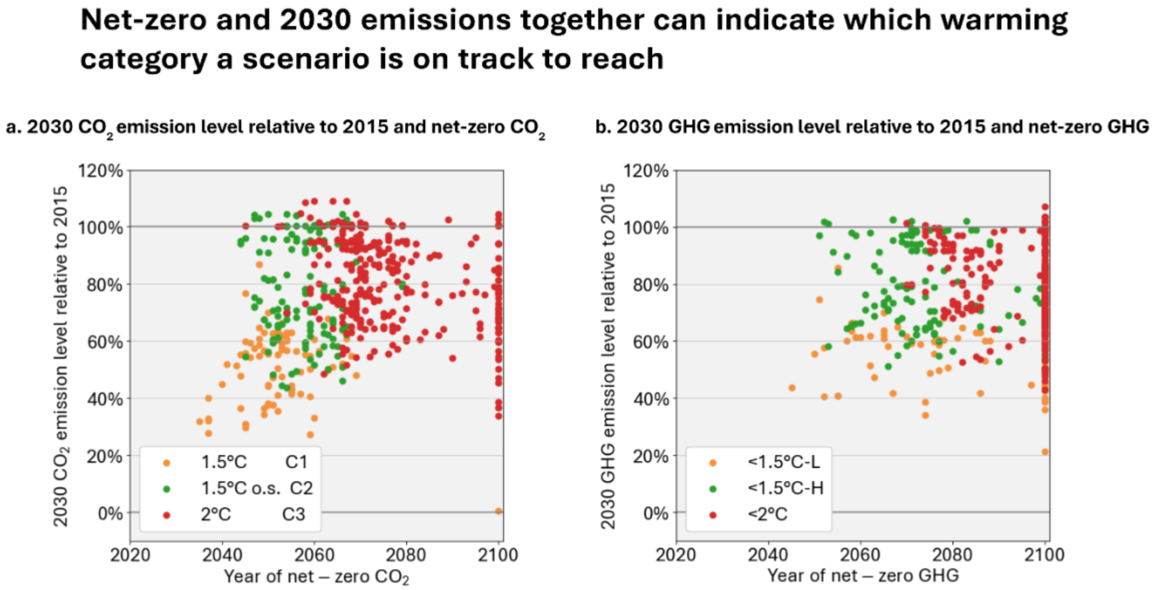

Figure 11 - 2030 CO_2 emission level compared to 2015 and the timing of net-zero CO_2

4.4. Net-zero and net-negative CO_2 emissions

4.4.1. Net-zero CO_2 and net-negative emissions

There is no clear relationship between negative emissions and the net-zero year for 1.5°C scenarios. Here, the most important impact is related to the level of temperature overshoot. If no real overshoot is allowed (C1 and C3), some relationship between net negative emissions and net-zero year emerges. The extent of cumulative net-negative emissions greatly differs between on the one hand both 1.5°C and on the other hand the 2°C scenarios (Figure 12). The <1.5°C-L scenarios have a similar amount of net-negative emissions as the <1.5°C-H scenarios, but net-zero is reached earlier.

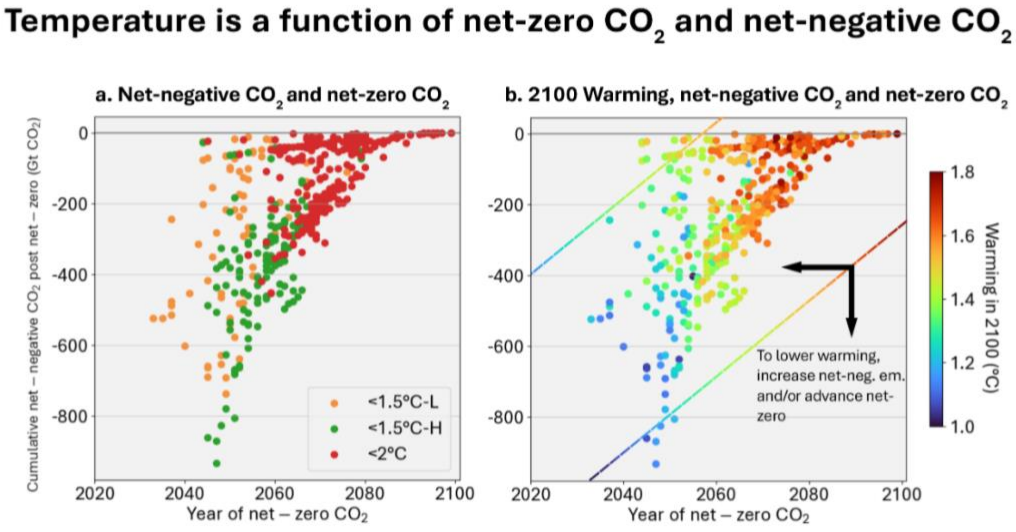

Figure 12 - Cumulative net-negative emissions and net-zero CO_2

4.5. Net-zero and conversion metric

4.5.1. (Ex-post) measuring net-zero GHG with different conversion metrics

Net-zero GHG calculated with GWPs over different time horizons are decades apart. However, net-zero GHG calculated with GWP-100 from different IPCC reports are only shifted slightly.

Figure 13 shows how the timing in net-zero GHG is shifted by decades when applying the GWP variants. GWP-20 will shift the timing of net-zero GHG further away from net-zero CO_2 by weighing mainly CH_4 much more strongly, to the extent that most scenarios do not reach net-zero GHG anymore.

GWP-500 will shift the timing of net-zero GHG closer to net-zero CO_2 by weighing CH_4 and N_2O less. Using GWP-500 therefore makes net-zero GHG easier to achieve. Countries should therefore always indicate which conversion metric they are using to calculate net-zero GHG.

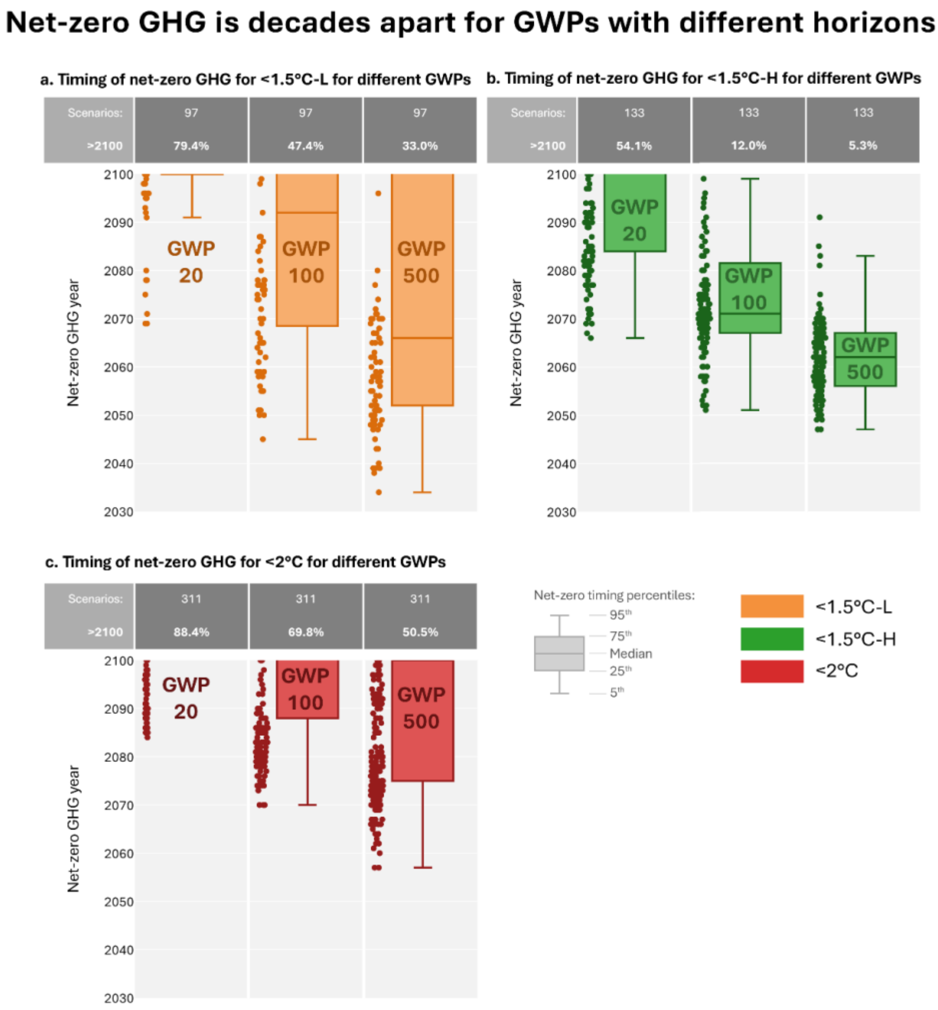

Figure 13 - Timing of net-zero GHG for the three warming categories under GWP-20, GWP-100, and GWP-500 from AR5

Figure 14 shows the timing of net-zero GHG under GWP-100 from SAR, AR5, and AR6. The differences between these different GWP-100 variants can be up to a few years. Currently this difference is relatively small, but it might increase as GWP-100 is increased in next assessment reports. Countries should therefore always indicate which GWP-100 variant is used for their net-zero GHG target.

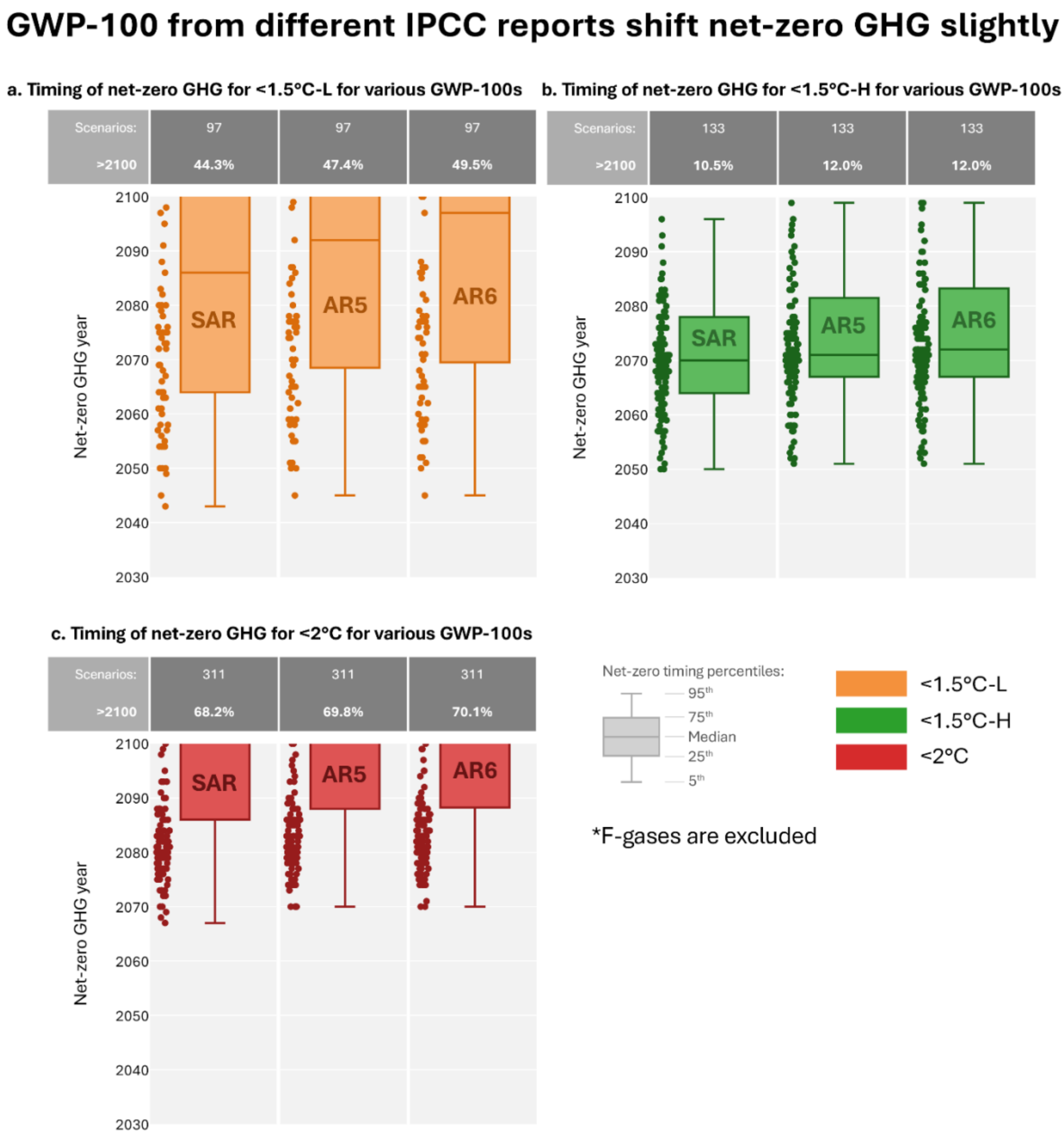

Figure 14 - Timing of net-zero GHG for the three warming categories under GWP-100 from SAR, AR5, and AR6

4.5.2. (Ex-ante) Impact of different conversion metrics on net-zero GHG

Applying different GWP metrics ex-post, as done above, does not give a complete picture: it ignores that emissions of separate GHGs would have been different if the different GWP metrics would also have been applied when constructing the scenarios. Therefore, we also conduct an ex-ante analysis, in which scenarios are developed with different conversion metrics.

Different GWPs shift the timing of net-zero GHG by many years and the timing of net-zero CO_2 by a few years. The isolated effect of different GWPs on the CH_4 price and timing of net-zero is only minor (Figure 15).

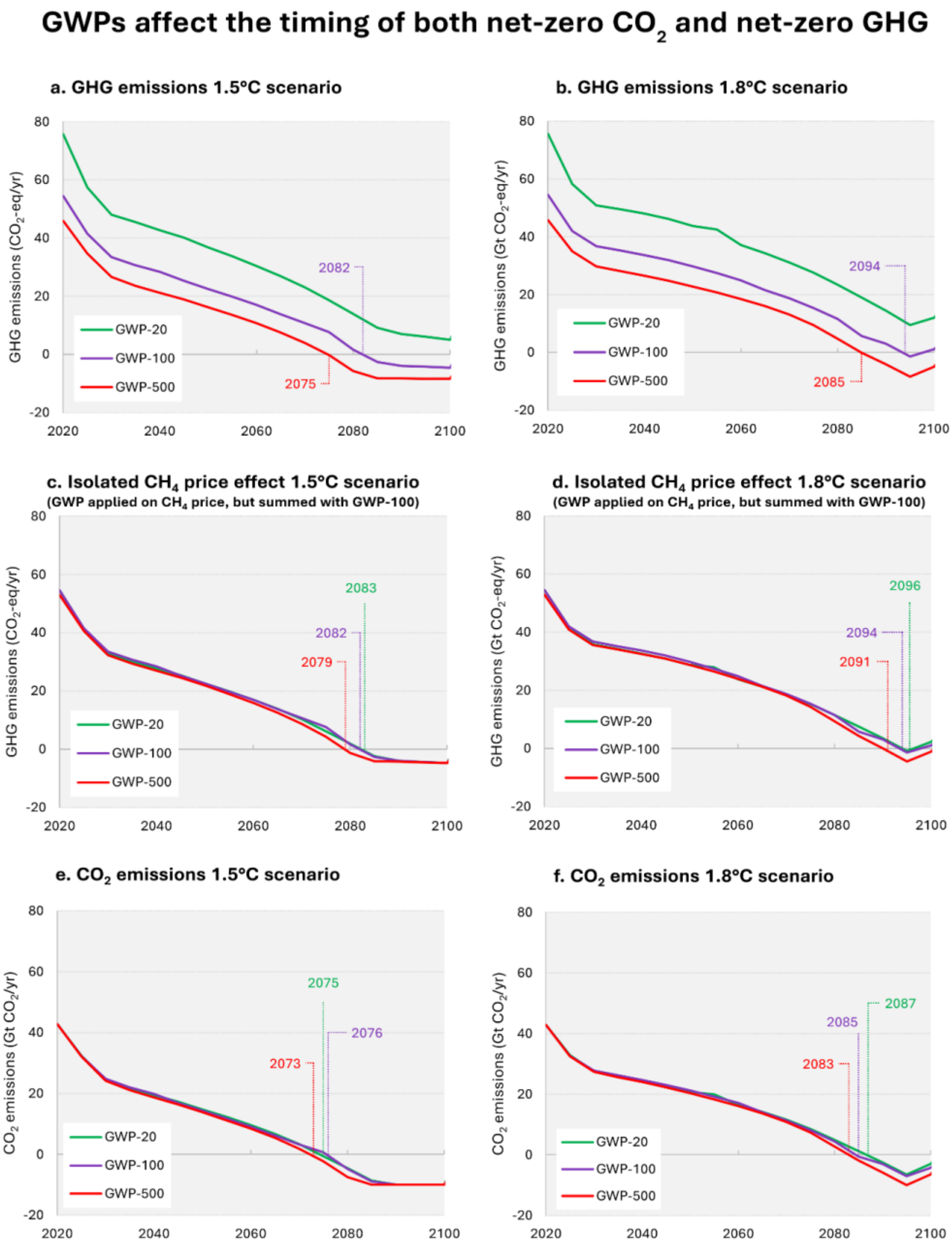

Figure 15 - GHG and CO_2 emissions for 1.5°C and 1.8°C scenarios using GWP-20, GWP-100, and GWP-500

We find that this does not change the result by much, as methane emissions are mitigated to their maximal potential even when applying relatively low GWP values for methane. This is caused by the two effects that the GWP can have on a scenario.

First, a lower GWP value creates a lower CH_4 price, which makes CO_2 preferable to abate first. However, this effect is quite minor. Second, a lower GWP value weighs CH_4 less, thereby lowering the GHG emission value in terms of CO_2-eq.

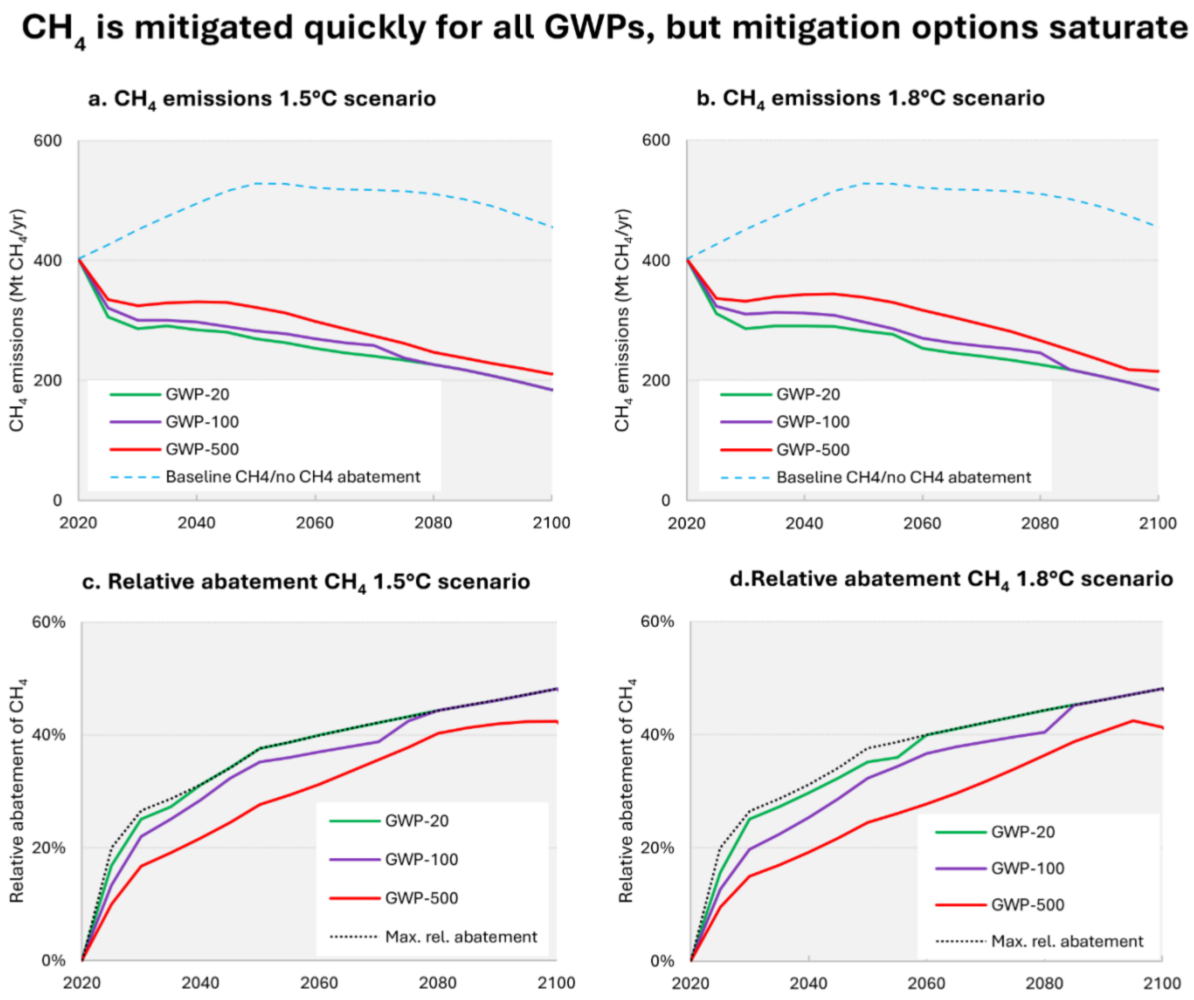

Figure 16 - CH_4 emissions and relative abatement of CH_4 for 1.5°C and 1.8°C scenarios

All scenarios tend to reduce CH_4 quickly compared to the baseline emissions, because many CH_4 mitigation options are relatively cheap and reduce warming strongly. On top of that, the CH_4 price becomes high enough that many more expensive mitigation options are used. In the 1.5°C scenario with GWP-20, all possible CH_4 mitigation options are saturated around 2040. Only the learning-over-time unlocks more CH_4 mitigation options, which are then also immediately saturated. For the 1.5°C scenario with GWP-100 and the 1.8°C scenarios with GWP-100 and GWP-20 we see similar trends, although saturation of mitigation options only occurs a few decades later. GWP-500 scenarios never reach mitigation saturation because of its lower GWP value.

Overall, we observe that the differences in timing of net-zero GHG for the ex-ante analysis are relatively similar to the differences in timing of net-zero GHG in the ex-post analysis. This is because of the limited effect the GWP value has on CH_4 mitigation, which therefore only has a limited effect on the timing of net-zero GHG and net-zero CO_2. The effect that the GWP value has on weighing CH_4 when aggregating GHGs is much stronger.

4.6 Cost-optimal allocation of net-zero targets at country level

Earlier, van Soest et al. (2021) looked at a smaller data set of IAM results to see whether also national net-zero targets could be derived and whether they could find specific rules that would determine early and late net-zero years (based only on costs).

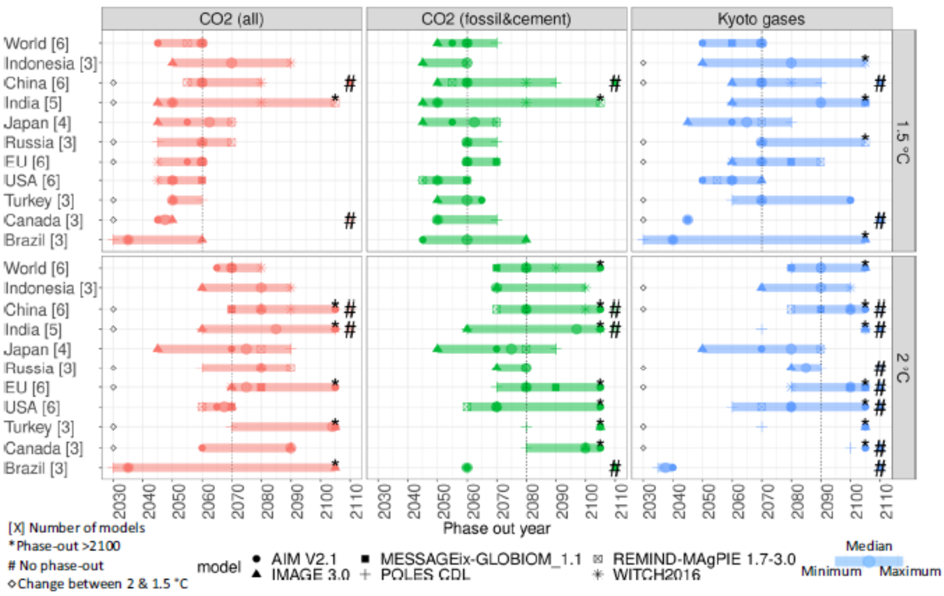

Figure 17 - GHG and CO_2 emissions for 1.5°C and 1.8°C scenarios using GWP-20, GWP-100, and GWP-500, from van Soest et al. (2021)

They found that domestic net zero greenhouse gas and CO_2 emissions in Brazil and the USA are reached a decade earlier than the global average, and in India and Indonesia later than global average. The results also showed that carbon storage and afforestation capacity, income, share of non-CO_2 emissions, and transport sector emissions affect the variance in projected phase-out years across countries. However, this would be based on only costs and an alternative method would be to establish target years based on equity-based rules.

5. Discussion

Lower warming requires earlier net-zero, but the relation is influenced by other factors

Cumulative CO_2 emissions are a key determinant of warming. As a result, also the net-zero year plays a key role. A lower 2100 temperature goal generally requires an earlier net-zero CO_2. This relation is the same for net-zero GHG, but many scenarios do not reach net-zero GHG while still limiting warming to a certain temperature. The 2100 temperature goal thus shifts the required timing of net-zero significantly. However, the relationship is also dependent on other parameters, such as the mitigation start, mitigation speed, and net-negative emissions.

Net-zero CO_2 is reached around the middle of the century of <1.5°C-L, around 2050-2060 for <1.5°C-H, and around 2070-2080 for <2°C scenarios. <1.5°C-L scenarios have some more room to slow down their transition after a rapid and not delayed start, such that they can be more flexible in their timing of net-zero CO_2.

But also overshoot plays a role. As current NDC pledges for 2030 only result in slightly lower emissions compared to 2015-2020, they cannot be combined with the <1.5°C-L class. To still reach 1.5°C by 2100 with some overshoot, the window in which net-zero CO_2 should be reached narrows to around 2050-2060.

Net-zero CO_2 is not a definite requirement for all <2°C scenarios, but this requires emissions to be reduced more quickly early in the century (and that the 2100 temperature are likely higher). Such scenarios might occur if it turns out that some sectors can decarbonize less than expected, or when CDR turns out to be less effective such that emissions stabilize at low levels just above net-zero CO_2. Figure 18 shows that those scenarios without net-zero CO_2 often start mitigation earlier, which can compensate for their lack of net-negative emissions. There is currently high uncertainty to what extent hard-to-abate sectors can be decarbonized and to what extent (net-)negative emissions can be deployed in the future. This makes focusing on reducing emissions as quickly as possible even more important, because in case CO_2 emissions cannot become negative the world runs the risk of ending up above the global temperature targets.

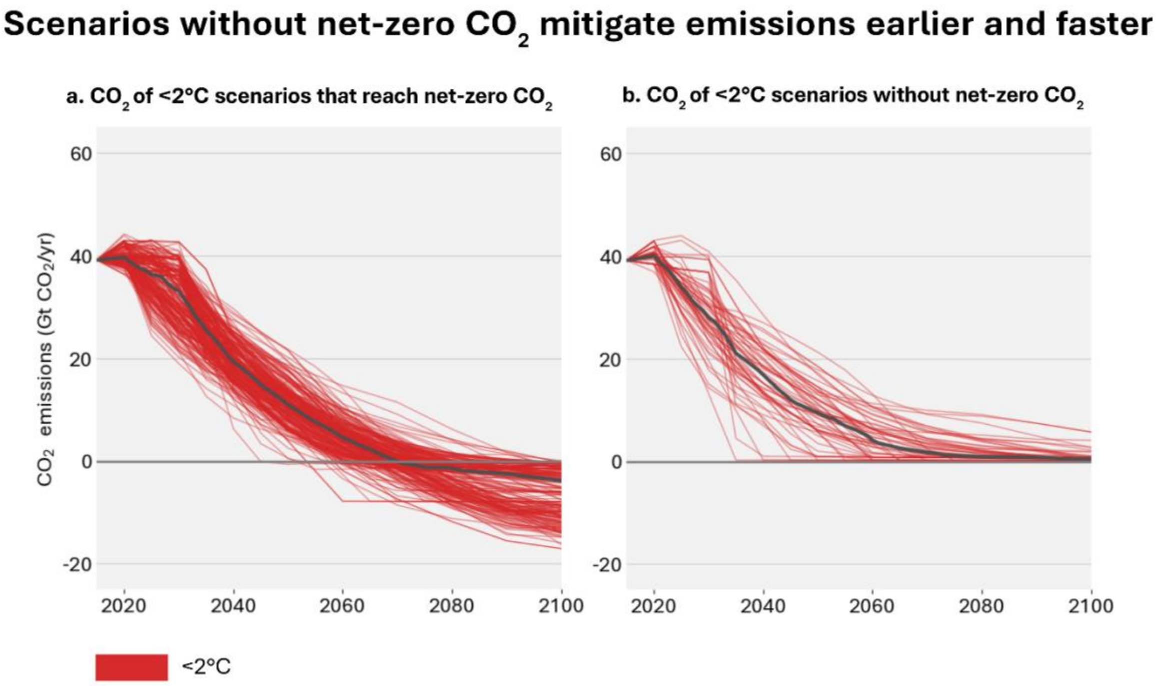

Figure 18 - <2°C scenarios with and without net-zero CO_2

Reaching net-zero GHG is important for <1.5°C-H scenarios, but less so for <1.5°C-L and <2°C scenarios. Still, many countries have set a national net-zero GHG target, and the Paris Agreement contains a net-zero GHG as well. The Paris Agreement and many national net-zero GHG targets are thus more in line with 1.5°C overshoot scenarios.

Net-zero is not only dependent on warming, but also on when large-scale mitigation begins, the mitigation speed, and extent of net-negative emissions. It is therefore important that, next to the timing of net-zero and temperature target, interim targets for both the short term and long term are established for any net-zero target.

The issue with IPCC's warming categorization

Lumping scenarios in warming categories (<1.5°C-L, <1.5°C-H, and <2°C in this study, C1-C3 in IPCC AR6) creates spread when plotting the timing of net-zero within these categories. The 2100 warming for scenarios within a single warming category can vary up to 0.5°C. The <1.5°C-L and <1.5°C-H categories contains scenarios between 1°C-1.5°C warming (50th percentile from MAGICC), and the <2°C category contain scenarios between 1.5°C-1.8°C warming (50th percentile from MAGICC). Figure 19 shows how the net-zero CO_2-warming ranges are wide for each category, but that the relationship between net-zero CO_2 and warming is quite linear. This indicates that some spread in the timing of net-zero as presented in this study and in the IPCC reports can be addressed to the lumping of scenarios within these categories. This categorization issue is a flaw in the way data is presented in this study but might be overcome in future studies by introducing more subcategories.

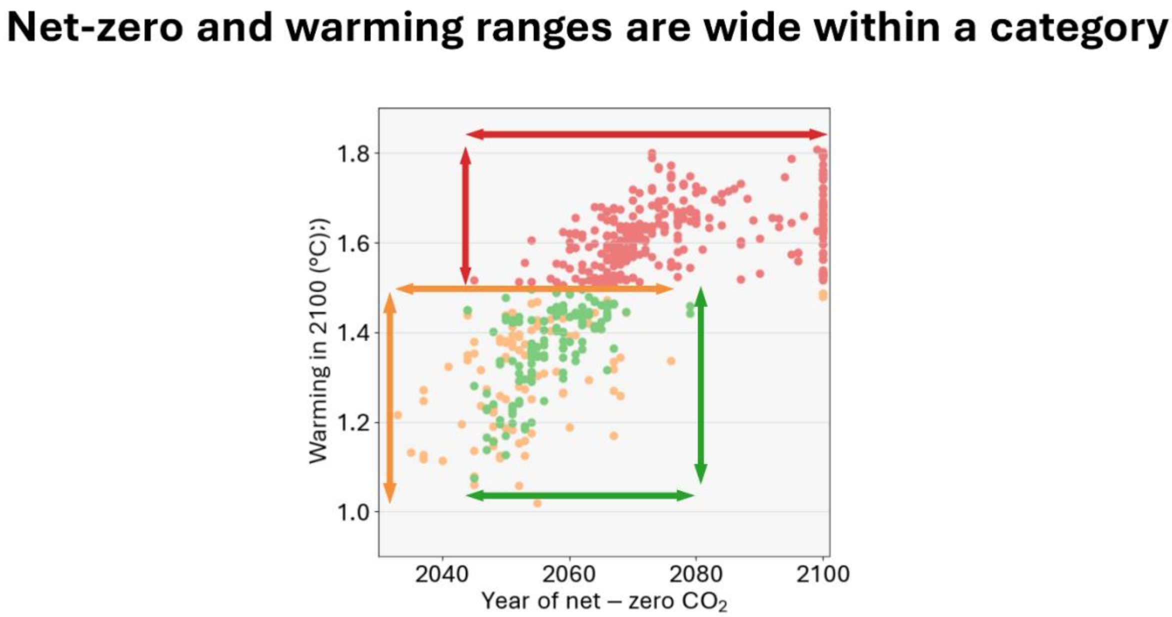

Figure 19 - Net-zero CO_2 year as a function of warming; arrows indicate ranges for net-zero and warming for warming categories

Net-zero emissions scope: under-promising in the short term, overpromising in the long term?

Many countries have set ambitious net-zero GHG targets in 2050, but current NDC pledges do not reflect this. It seems that countries are generally overpromising climate ambition in the long term but are generally under-promising in the short term compared to IPCC pathways related to the Paris Agreement.

Many national net-zero targets are currently more ambitious than the most ambitious IPCC scenario. Figure 20 shows that a large extent of global GHG emissions are covered by national net-zero GHG targets and some by national net-zero CO_2 targets. In this study we have shown that net-zero CO_2 is often reached one to two decades earlier than net-zero GHG. The IPCC has communicated that for the most ambitious scenario, 1.5°C without overshoot, global net-zero CO_2 should be reached between 2050-2055 and global net-zero GHG somewhere around 2095-2100. Many countries' net-zero targets are therefore more ambitious than the most ambitious IPCC scenarios. This, however, could be a conscious choice based on countries' historical emissions. Still, it is important to be aware of the large differences between net-zero CO_2 and net-zero GHG.

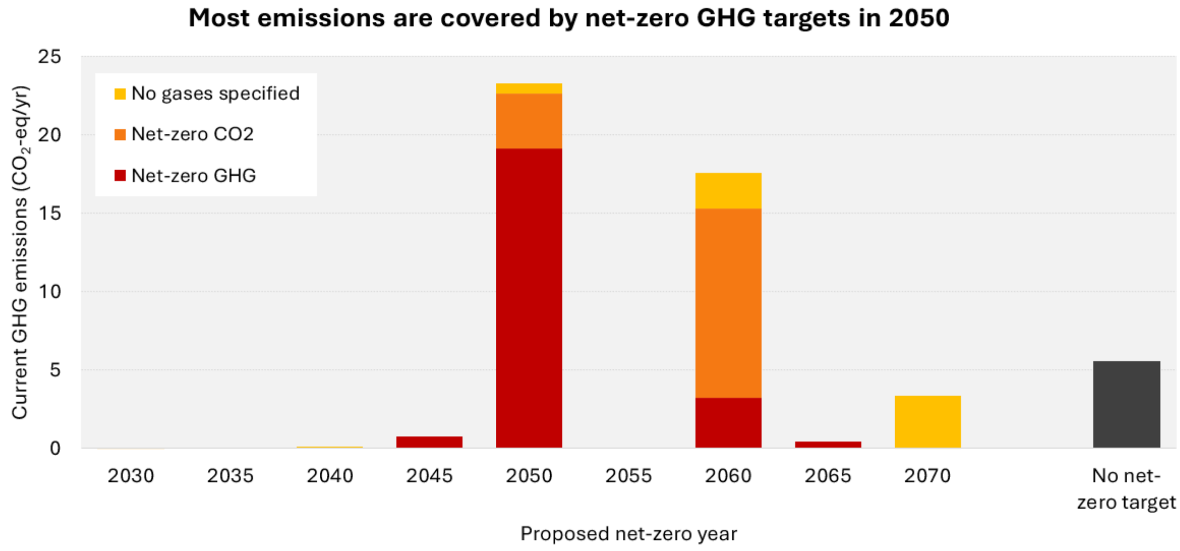

Figure 20 - Global emissions covered by different national net-zero targets

On the other hand, current NDC pledges will result in higher emissions in 2030 compared to 2021 emissions, which is a much less ambitious pathway than the <2°C scenarios. It seems that many countries overpromise with their net-zero targets in the long term and under-promise in the short term. This creates a gap, which puts the climate goals at risk (van Soest *et al* 2021a, Baptista *et al* 2022, den Elzen *et al* 2022).

Another issue with focusing on net-zero GHG in 2050 might be that these targets are so ambitious that they run the risk of not being reached at all. This is because scenarios that reach net-zero GHG generally require substantial negative emissions. Whether this is possible as early as 2050 is uncertain (Rogelj *et al* 2023).

Trade-offs for high 2030 emissions: earlier net-zero, more net-negative emissions, or accepting a higher temperature.

The current 2030 NDC pledges are not in line with <1.5°C nor <2°C scenarios. If no higher ambitions targets are set and emissions are only reduced after 2030, this will create a trade-off if global climate targets are to be reached. Will high 2030 emissions be compensated with net-negative emissions or by a faster (and potentially more chaotic) transition towards an earlier net-zero? If none of these are desired or possible, the world will likely reach a higher temperature.

To reach the same 2100 temperature but with high 2030 emissions, some scenarios have a slightly earlier net-zero and a faster mitigation rate. This might be risky, and a faster transition towards net-zero is potentially more disorderly.

Other scenarios compensate for high 2030 emissions with more net-negative emissions towards the end of the century, which might be undesirable given the high uncertainties surrounding CDR. Counting on one of these two options is risky. A more desirable options would likely to set higher ambition targets in the short term.

Alternatively, if lower 2030 emissions, more extensive net-negative emissions, or earlier net-zero with faster transition are either undesirable or not possible, the world will need to accept that it will likely reach a higher temperature by 2100.

IAM model preference for net-zero

The type of IAM model and scenario types they run can create spread in the timings of net-zero for scenarios. The most common IAMs used for <1.5°C-L, <1.5°C-H, and <2°C scenarios are various versions of REMIND, MESSAGE, and IMAGE[3]. The way these models are wired and which types of scenarios they run influences how they mitigate emissions and hence when they reach net-zero emissions. REMIND scenarios have a relatively large spread in the timing of net-zero CO_2 and net-zero GHG compared to MESSAGE and IMAGE (Figure 21). This pattern is visible for most warming categories and for both net-zero CO_2 and net-zero GHG.

The spread for REMIND scenarios might be inherent to the model, or it might be dependent on which specific scenarios are run using the model. For example, REMIND scenarios might run more diverse scenarios with many varying inputs. Although this is not analysed further in this study, the spread that is created by the models and scenarios creates some additional noise in the results of this study.

[3] For model descriptions, see the IAMC wiki: https://www.iamcdocumentation.eu/

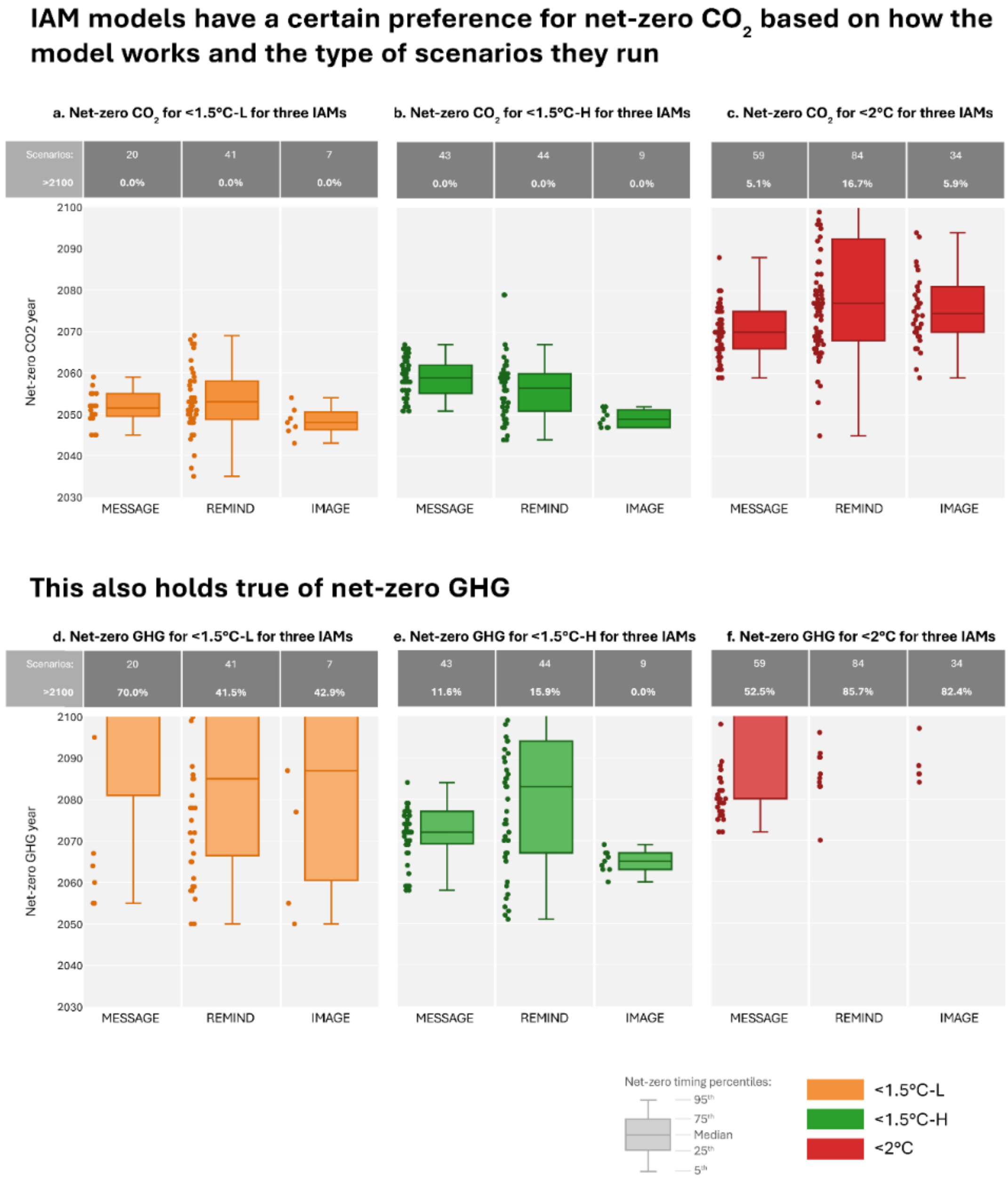

Figure 21 - Timing of net-zero CO_2 and net-zero GHG for MESSAGE, REMIND and IMAGE

Differences in total costs for different GWP horizons are small

The type of MAC curve used, and the uncertainties therein will be an important factor for when net-zero CO_2 and GHG are reached, also for mitigation pathways in general. For this study we applied a MAC curve with default assumptions about the development of non-CO_2 mitigation options (Harmsen *et al* 2019), but a more recent study from the same authors has shown that there are many uncertainties for these non-CO_2 mitigation options, to the extent that ambitious temperature targets might not be reached (Harmsen *et al* 2023). Since we have found that CH_4 mitigation options tend to saturate for all scenarios with GWP-100 and GWP-20, the MAC curve assumption is especially important for not only the timing of net-zero, but for mitigation pathways in general.

An additional observation we make is that total mitigation costs do not differ significantly between GWP scenarios (Figure 22).

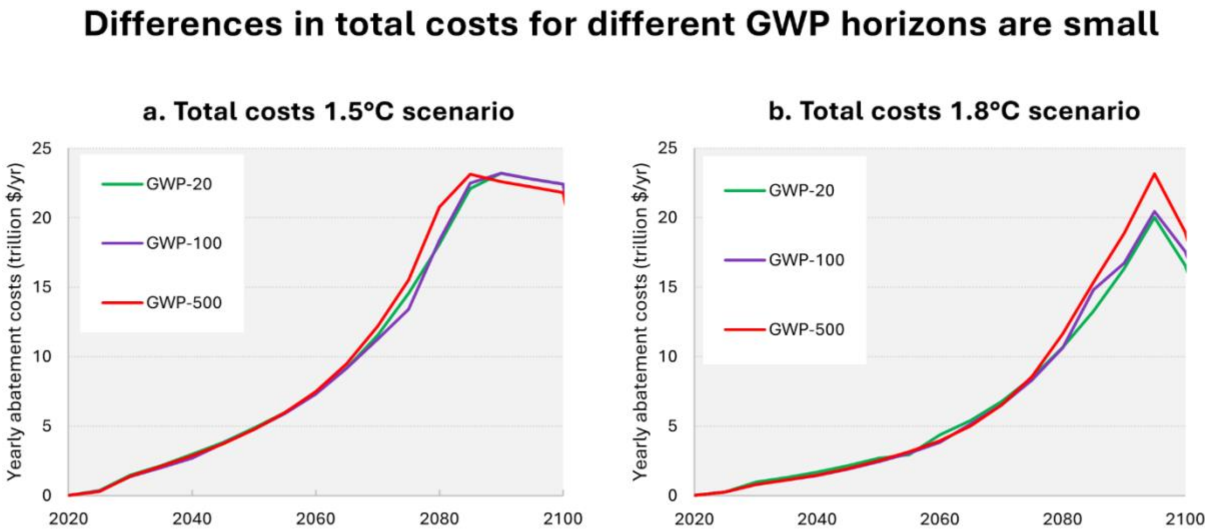

Figure 22 - Total abatement costs of CO_2 and CH_4 combined

Limitations of this study

On top of the warming categorization and model-scenario spread that introduce some limitations to this study, we here present some other limitations. We also present some ideas on how these limitations could be overcome in further studies.

- Methods: no exact quantification

The methods applied here of plotting differing scenarios and comparing their differences was focused on describing the differences between scenarios instead of exactly quantifying the differences. For further studies, some type of t-test or ANOVA could be performed.

- Global scope of this study

This study is focused on the global level. Since each country has a different proportion of CO_2 and non-CO_2 emissions, this will create different shifts in the timing of net-zero for its different formulations. The results in this study can therefore best be used as guide for what different formulations of net-zero could potentially imply on the national level.

- Other components of net-zero not considered in this study

This study considers many components of net-zero but leaves out two important ones. First, we do not consider the impact of using national greenhouse gas inventories to count emissions instead of global models. Global CO_2 emissions from national greenhouse gas inventories are lower by 5.5 $GtCO_2$/yr compared to global models, due to different ways of accounting for land-use CDR on the national level. This will have some impact on the timing of net-zero CO_2 and net-zero GHG. Due to time constraints, this component was not covered here.

This study also does not include equity and fairness principles and their effect on net-zero, mainly because this study was performed on the global scale. On a regional level, the way the burden of emission reduction should be shared will have important consequences for the timing of net-zero.

- MIMOSA limitations

The MIMOSA model is a simple IAM and thus leaves out many detailed global processes. The addition of GWP* and simple climate model is another simplification added to MIMOSA. In this case, we have assumed that the relation between cumulative CO_2, cumulative CO_2-we emissions and the TCRE give a decent estimation of global temperature based on previous studies (Lynch *et al* 2020). However, we have not tested the accuracy of this relation here. In future studies, the emissions of a MIMOSA run could be fed to MAGICC, such that the temperature outcomes can be compared.

Another limitation is that we only introduced CH_4 into the model and not other non-CO_2 GHGs, such as N_2O and F-gases. However, using the same methods as this study used for introducing CH_4 into MIMOSA, N_2O and F-gas could also be added, using e.g., the MAC curves from Harmsen et al. (2019).

The default MIMOSA model includes some non-CO_2 abatement in its CO_2 MAC curve. Since we have introduced a MAC curve on top of this, CH_4 abatement is currently counted double. This might be improved in newer versions of the model.

We also did not use the latest CH_4 MAC curve from the same authors. Their new MAC curve introduces uncertainty related to non-CO_2 abatement and includes an optimistic, pessimistic, and default MAC curve. Since CH_4 mitigation options saturate for GWP-20 and GWP-100 scenarios, it will likely make a difference whether an optimistic, pessimistic, or default MAC will be used. This will also have consequences for the timing of net-zero.

6. Conclusion

The timing of net-zero shifts based on the way net-zero is defined, sometimes by multiple decades. It is therefore important to be aware of the implications of the differences in timing between different formulations of net-zero.

The timing of net-zero is strongly related to warming. This is especially the case for net-zero CO_2. Net-zero CO_2 for <1.5°C-L is around the middle of the century. For <1.5°C-H this is around half a decade later, but the timeframe in which it should be reached becomes stricter. For <2°C net-zero CO_2 is reached somewhere in the second half of the century with considerable spread for different scenarios. Some <1.5°C-L and <2°C scenarios never reach net-zero CO_2, but these scenarios stabilize emissions at a low level close to net-zero CO_2.

Although net-zero GHG is not reached in many scenarios, it is important as temperatures overshoot and more (net-)negative emissions are required. This is the case for many <1.5°C-H scenarios. Scenarios with less (net-)negative emissions (<1.5°C-L) and/or higher warming (<2°C) often do not reach net-zero GHG.

Net-zero CO_2 is often reached decades earlier than net-zero GHG. On a global level, this means that global net-zero CO_2 should be reached a few decades prior to the net-zero GHG target set out in the Paris Agreement. This also holds for countries who have set only a net-zero GHG target.

High 2030 emission scenarios require an even more rapid transition towards an earlier net-zero and/or more extensive negative emissions to limit warming to a certain goal. For <1.5°C-H scenarios, net-zero CO_2 is reached only a few years earlier after high 2030 emissions, but these high 2030 emissions are offset with extensive negative emissions. Net-zero GHG is also reached more often in these scenarios. Both net-zero CO_2 and net-zero GHG is reached more often and earlier in <2°C scenarios after high 2030 emissions, caused by the faster transition and more extensive net-negative emissions required to compensate for the earlier high emissions.

Net-zero is strongly linked to net-negative emissions and warming. Extensive net-negative emissions can compensate for a later net-zero year. For the same warming level, scenarios with extensive net-negative emissions can reach net-zero CO_2 around one to two decades later. This means that if lower levels of net-negative emissions are desired, net-zero CO_2 should be advanced. It also means that net-zero GHG does not necessarily need to be reached if lower net-negative emissions are desired.

The GWP metric over different time horizons has a large impact on the timing of net-zero GHG. The GWP metric from different reports only shifts net-zero GHG around half a decade. The differences between GWPs over time horizons of 20, 100, and 500 years are around one to two decades between each other. By using GWP-20, net-zero GHG is only reached in a small percentage of scenarios.

The timing of net-zero is dependent on many factors, many of which pose trade-offs and considerations for target setters. This study has pointed to various components of net-zero which are important to consider for global net-zero policy and national net-zero policy:

- A net-zero target should disclose which temperature target it is contributing to. Different temperature targets require a different timing of both net-zero CO_2 and net-zero GHG.

- A net-zero target should always disclose the emission scope, because the difference between the timing of net-zero CO_2 and net-zero GHG is often decades. Ideally, if a net-zero GHG target is set, also a net-zero CO_2 should be set at some point before net-zero GHG.

- The timing of net-zero is strongly dependent on the pathway towards and after it. This means that if emissions earlier in the century, such as in 2030, are higher, this needs to be compensated for by a faster transition towards an earlier net-zero, and/or compensated for by more extensive net-negative emissions. Ideally, interim targets are set for before and after net-zero.

- A net-zero target should disclose the conversion metric it uses. The GWP metric over different horizons can shift the timing of net-zero GHG by multiple decades and the GWP-100 value from different IPCC assessment reports shifts the timing of net-zero GHG by several years.

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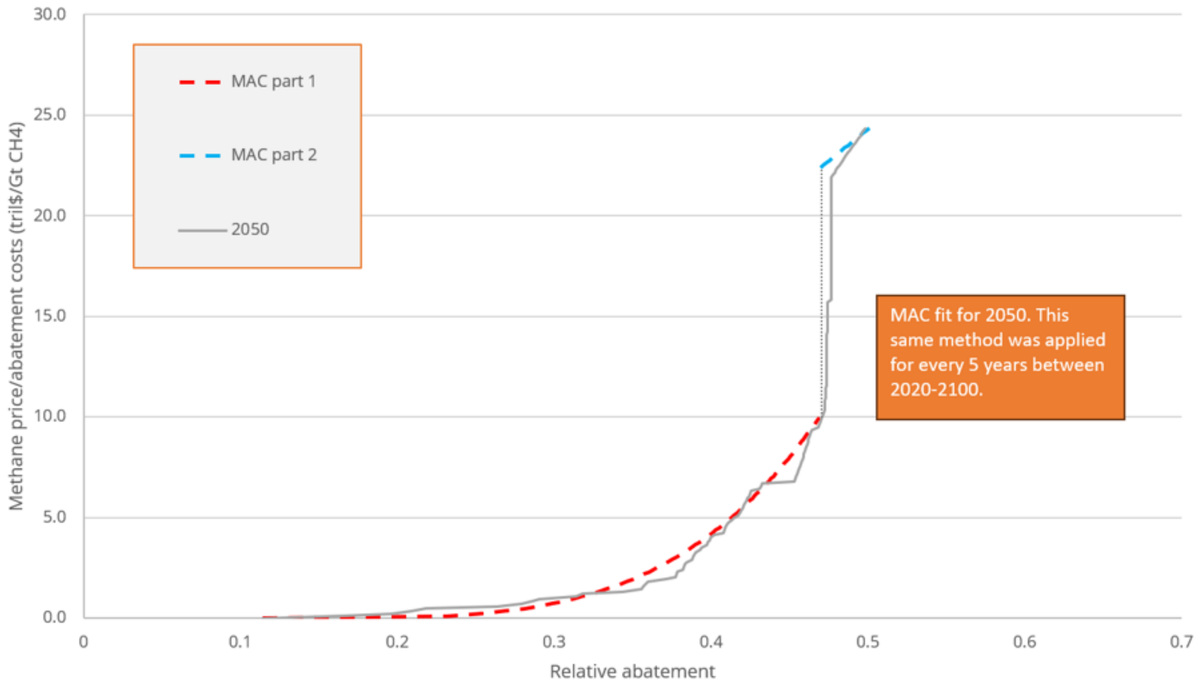
Appendix I



MAC curve fitting