A guide to scenarios for the PROVIDE project

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Project: PROVIDE – Paris Agreement Overshooting – Reversibility, Climate Impacts and Adaptation Needs
Document date: 8 July 2022

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101003687.

Overview of scenarios

- 10 Tier 1 scenarios until 2100
- 15 Tier 1 scenarios defined until 2300, all of which are variations of the original 10
- Many Tier 2 scenarios, aiming to completely tile reasonable emissions space parameterised with 4 variables

1. Summary

Several objectives of the PROVIDE project depend on a set of scenarios that can be modelled through either a 'classical' forward-looking approach or by a novel approach that 'reverses the impact chain'. These scenarios are also key elements for the integration of PROVIDE findings in the outward-looking stakeholder Dashboard of the project. Here we describe the set of scenarios that has been developed and will be used within PROVIDE. In total, PROVIDE explores ***three complementary approaches****:*

1) *10 distinct tier 1 scenarios extending until 2100, mostly based on the existing literature, used for short-term assessments of impacts*
2) *15 distinct tier 1 scenarios extending until 2300, based on different extensions of the 10 literature scenarios, used for assessing longer-run impacts and the geophysical impact of significant temperature overshoot*
3) *~1350 distinct tier 2 scenarios, exploring several dimensions of emissions space systematically, such as CO_2 net zero date and relative methane intensity. This is used to explore which scenarios are compatible with given climate outcomes. These scenarios can be used to reverse the traditional impact chain, going from acceptable climate risks to descriptions of acceptable emissions.*

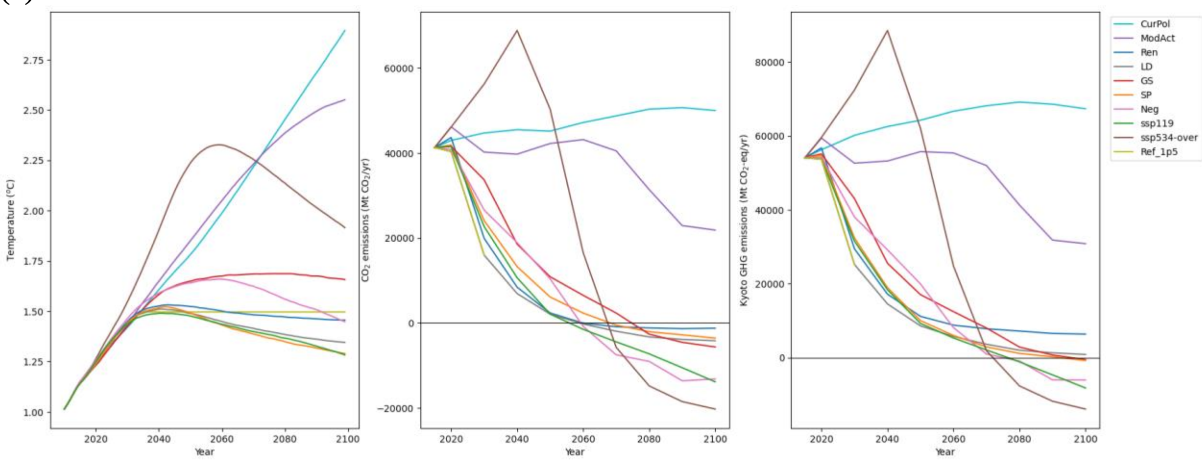
2. Tier 1 Scenarios

A **core idea** of the scenario design under PROVIDE is that global surface temperature (GMT) trajectories rather than emission or concentration pathways are the defining features for assessing climate impacts. This design choice allows us to compare impacts as a function of GMT between different models and approaches. Seven Tier 1 scenarios are based on the IPCC's Illustrative Mitigation Pathway (IMP) scenarios, two are from extensions to the Shared Socioeconomic Pathways (SSPs), and one is defined almost entirely in temperature space.

Within PROVIDE, GMT trajectories of both medians and selected quantiles will be provided for each of the Tier 1 scenarios, derived with Simple Climate Models (SCMs). In addition, multi-GHG pathways will also be provided as well as linked marker scenarios from the SSPs for spatially explicit forcing for aerosols in due course. The temperature, CO_2 and total Kyoto emissions for Tier 1 scenarios are plotted in figure 1.

Tier 1 scenarios are of higher importance for impact assessment than the Tier 2 scenarios.

(a)



(b)

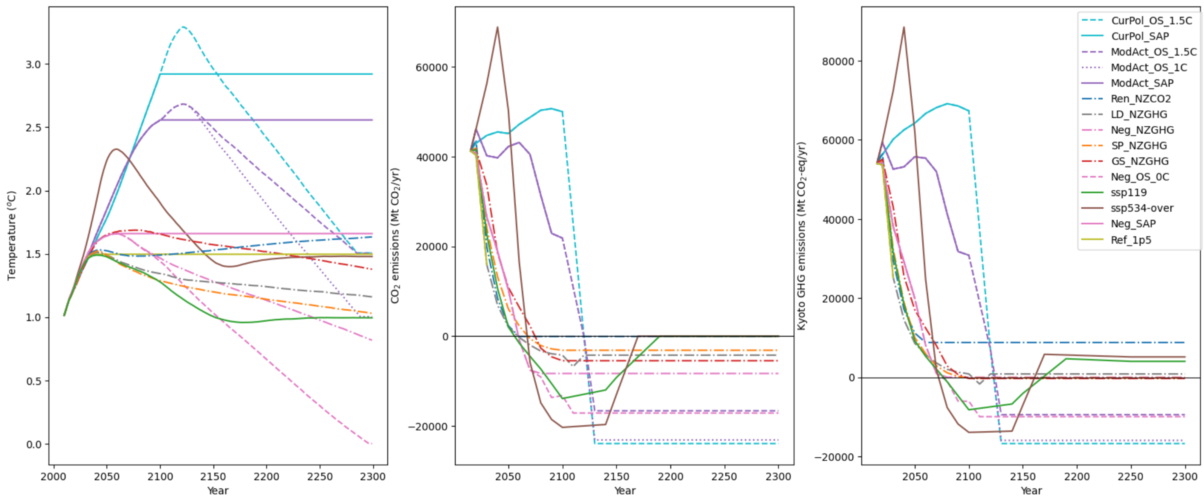


Figure 1: TIER 1 PROVIDE scenario characteristics for (a) pre-2100 scenarios (b) scenarios extending until 2300

Table 1: TIER 1 PROVIDE scenario characteristics for pre-2100 scenarios

#	**Scenario name**	**Running until**	**Start scenario**	**Description of modifications**
1	CurPol	2100	CurPol	Original scenario from (NGFS, 2020) obtained from AR6 WG3 scenario database (Byers *et al.*, 2022)
2	ModAct	2100	ModAct	Original scenario from (Riahi *et al.*, 2021) obtained from AR6 WG3 scenario database
3	GS	2100	GS	Original scenario from (van Soest et al., 2021) obtained from AR6 WG3 scenario database
4	NEG	2100	NEG	Original scenario from (GNFS, 2020) obtained from AR6 WG3 scenario database
5	REN	2100	REN	Original scenario from (Luderer et al., 2021) obtained from AR6 WG3 scenario database
6	LD	2100	LD	Original scenario from (Grubler et al., 2018) obtained from AR6 WG3 scenario database
7	SP	2100	SP	Original scenario from (Soergel et al., 2021) obtained from AR6 WG3 scenario database
8	Ref_1p5	2300	LD	Follow LD until the median global surface temperature increase reaches 1.5°C, and keep the entire surface temperature distribution constant thereafter
9	SSP5-3.4-OS	2300	SSP5-3.4-OS	Extension of (O'Neill et al., 2016) from RCMIP (Meinshausen et al., 2020)
10	SSP1-1.9	2300	SSP1-1.9	Extension of (Rogelj et al., 2018) from RCMIP

Table 2: TIER 1 PROVIDE scenario characteristics

#	Scenario	Running until	Start scenario	Description of modifications
1	CurPol_SaP	2300	CurPol	Keep 2100 global surface temperature distribution constant until 2300
2	CurPol_OS	2300	CurPol	- Fossil fuel & industry CO_2 emissions: decline to zero between 2100 and 2120, subsequently scale to a net negative level required to return median global warming to 1.5°C in 2300. - AFOLU CO_2 emissions decline to the level of the NEG pathway in 2100 and are kept constant at that level - Non-CO_2 emissions: linearly transition, between 2100 and 2120, to the respective 2100 non-CO2 GHG and aerosol emissions in IPCC_NEG and kept constant at that level thereafter until 2300
3	ModAct_SaP	2300	ModAct	Keep 2100 global surface temperature distribution constant until 2300
4	ModAct_OS_1.5C	2300	ModAct	- Fossil fuel & industry CO2 emissions: decline to zero between 2100 and 2120, subsequently scale to a net negative level so as to return median global warming to 1.5°C in 2300. - AFOLU CO_2 emissions decline to the level of the NEG pathway in 2100 and are kept constant at that level - Non-CO_2 emissions: linearly transition, between 2100 and 2120, to the respective 2100 non-CO_2 GHG and aerosol emissions in NEG_OS and kept constant at that level thereafter until 2300
5	ModAct_OS_1C	2300	ModAct	- Fossil fuel & industry CO_2 emissions:: decline to zero between 2100 and 2120, subsequently scale to a net negative level so as to return median global warming to 1.0°C in 2300. - AFOLU CO_2 emissions decline to the level of the IPCC_NEG pathway in 2100 and are kept constant at that level - Non-CO_2 emissions: linearly transition, between 2100 and 2120, to the respective 2100 non-CO_2 GHG and aerosol emissions in IPCC_NEG_OS and kept constant at that level thereafter until 2300
6	SSP5-3.4-OS	2300	SSP5-3.4-OS	None - following extension as in Meinshausen et al (2021)
7	SSP1-1.9	2300	SSP1-1.9	None - following extension as in Meinshausen et al (2021)

8	GS_NZGHG	2300	GS	Follow GS until net zero greenhouse gas (GHG) emissions in the AR6 GWP-100 metric are reached (interpolate between year 2098 and 2099) and keep emissions and aerosols constant at that level thereafter until 2300.
9	NEG_SaP	2300	NEG	Keep global surface temperature distribution constant at its peak value until 2300
10	NEG_OS_0	2300	NEG	- Fossil fuel & industry CO_2 emissions: decline to zero between 2100 and 2120, subsequently scale to a net negative level so as to return median global warming to 1.5°C in 2300. - AFOLU CO_2 emissions decline to the level of the NEG pathway in 2100 and are kept constant at that level - Non-CO_2 emissions remain at 2100 levels
11	NEG_NZGHG	2300	NEG	Follow NEG until net zero greenhouse gas (GHG) emissions in the AR6 GWP-100 metric are reached and keep emissions and aerosols constant at that level thereafter.
12	REN_NZCO2	2300	REN	Follow REN until net zero total CO_2 is reached and keep emissions and aerosols constant at that level thereafter until 2300.
13	LD_NZGHG	2300	LD	Follow LD until 2100. Then impose net zero greenhouse gas (GHG) emissions by reducing CO_2 from fossil fuel & Industry by 2110 and keep other emissions constant until 2300.
14	SP_NZGHG	2300	SP	Follow SP until net zero greenhouse gas (GHG) emissions in the AR6 GWP-100 metric are reached and keep emissions and aerosols constant at that level thereafter until 2300.
15	Ref_1p5	2300	LD	Follow LD until the median global surface temperature increase reaches 1.5°C, and keep the entire surface temperature distribution constant thereafter until 2300

Table 3: description of policy and socioeconomic assumptions behind the scenarios until 2100.

Scenario	Description
CurPol	Current policy pathway. This pathway explores the consequences of continuing along the path of implemented climate policies in 2020 with only mild strengthening after that. The scenario illustrates the outcomes of many scenarios in the literature that project the outcomes of current policies.
ModAct	Moderate action pathway. This pathway explores the impact of countries sticking to their Nationally Determined Contributions (NDCs) as stated in 2020. These are often more ambitious than currently implemented policies, but for most countries do not ratchet up very rapidly. Similar levels of mitigation effort are expected going forwards.
GS	Gradual strengthening pathway. Energy demand is reduced in the 2030s and the transition to variable renewable energy accelerates then too. Renewable energy never forces out all fossil fuel use – carbon dioxide is captured from the air and buried instead, along with reforestation.

Neg	Pathway with highest negative emissions (carbon-removing technology). Fossil fuel use decreases slowly, replaced about equally by variable renewable energy and biofuels. The carbon from burning the biofuels is captured and buried, offsetting the continued fossil fuel use.
Ren	Renewable pathway. Energy demand is reduced rapidly in the short-term, though grows later. Growth in renewables is very rapid and squeezes out most all other types of energy. Some biofuel is used to balance renewable variability, and the emissions from this are captured and buried.
LD	Demand-limiting pathway. Energy demand is massively reduced by implementing energy efficient lifestyles and design, and kept low throughout the century. Renewable energy grows and gradually forces out fossil fuels.
SP	This 'Shifting Pathways' scenario explores how a broader shift towards sustainable development can be combined with climate policies consistent with keeping warming to 1.5˚C. Energy demand is reduced over time, while renewable energy use grows, squeezing out fossil fuel use.
SSP1-1.9	Renewable energy is deployed rapidly. Energy demand is also limited rapidly. There is general focus on sustainability, but also a significant increase in the amount of biofuel use, with the carbon released by this captured and stored (negative emissions).
SSP5-3.4-OS	Carbon emissions rise at an incredibly fast rate in the short term. Then, around 2040 they decline extremely rapidly through the massive use of negative emissions technologies (for example capturing carbon from biofuel burning or directly from the air, and burying it). This pathway was designed to test the sensitivity of the Earth System to such extreme changes in emissions.
Ref_1.5C	Temperatures rise as in the demand-limiting case (LD) until the global average reaches 1.5°C. The temperature is then held constant. This scenario is a simple thought-experiment not driven by economic or climatic considerations.

Mapping on different overshoot characteristics

The scenarios are designed to explore a range of **different near-term, peak warming and overshoot outcomes** and are extended until 2300 to allow for a systematic assessment of long-term outcomes. We include scenarios exceeding 2.5°C then returning to 1.5°C and 1°C, as well as a low overshoot pathway that peaks at 1.8°C and returns to pre-industrial levels of warming by 2300.

3. Tier 2 Scenarios

Multiple scenarios are using stylized assumptions to systematically map a reasonable emissions space, loosely based on the range of values of net-zero scenarios in the SR1.5 database of scenarios that decline in emissions after 2030.

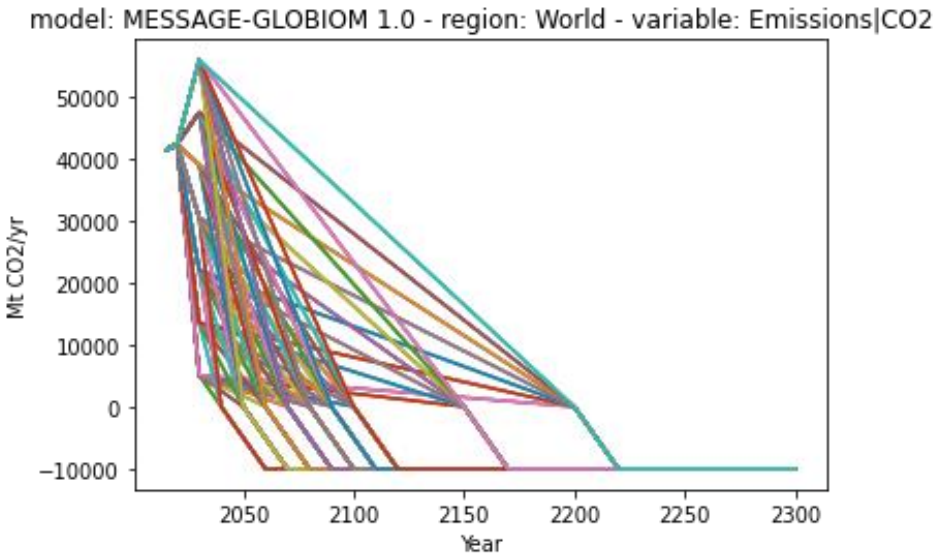
Table 4: Tier 2 scenarios

Pathway characteristic	Options	Granularity (# options)
2030 emission levels	Between 4542 and 59709 Mt CO_2/yr	6
Net zero CO_2 date	Dates between 2040-2100 decadally, plus 2150 and 2200	9

CDR levels	0 - -10000 Mt CO_2/yr (Net)	5
Methane assumptions	Determined by quantiles within the relationship between methane in a given year and CO_2, using the Quantiles Rolling Window (QRW) method from the Silicone package (Lamboll et al. 2020). Quantiles 0.1, 0.25, 0.5, 0.75 and 0.9 used.	5
Post 2100	Everything except CO_2 continues at the same level. CO_2 completes its trend past net zero towards its long-term carbon extraction goal.	1

Key factors:
Scenarios are parameterised via net-zero date, 2030 emissions level, net CDR removal and methane response (which also depends on the level of CO_2 emissions). We assume a linear reduction in CO_2 between 2030 and the chosen net-zero date. CO_2 then descends to the CDR level at a gradient no faster than the fastest descent found in the SR1.5 database. All other emissions are based on relationships between greenhouse gases and other climate forcers as found in the full set of scenarios in the SR1.5 database, and kept constant after 2100. The open-source package Silicone is used to this end.

(a)



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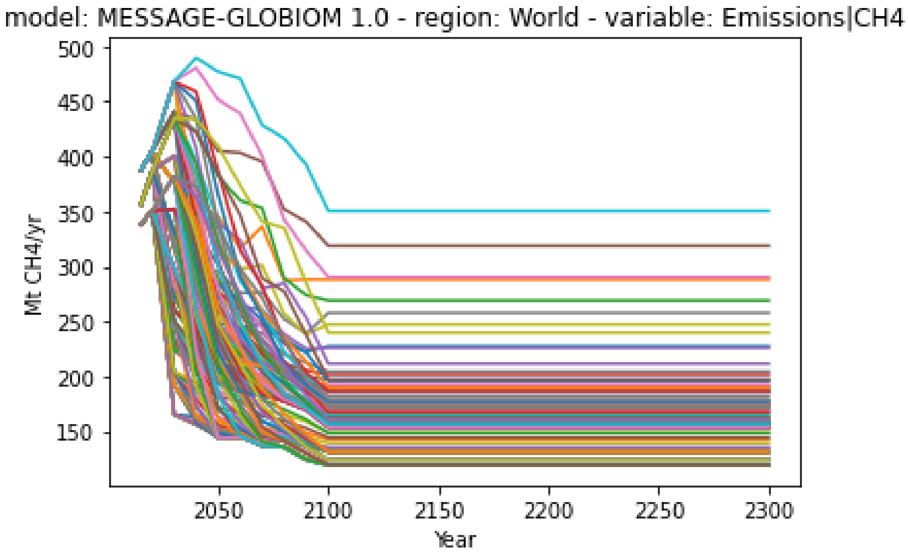

Figure 2: Example emissions trajectories for Tier 2 scenarios, for a) CO_2 b) methane. This particular subset of Tier 2 scenarios descends to one level of CDR (10 $GtCO_2$/yr) only, while the entire set also includes 5 levels from 0 to 10 $GtCO_2$/yr (see Table 4)

4. Key research questions related to overshoot

Table 5: the set of questions that we plan to ask concerning the impacts of overshoot pathways, and how we can resolve them using the PROVIDE pathways.

#	Overshoot research questions	Useful PROVIDE scenarios
1	What is the difference between (a) permanently exceeding 1.5°C and stabilising at a higher level, (b) stabilising at 1.5°C of warming, (c) peaking above 1.5°C and returning to 1.5°C in either 2100 or 2300?	Full set of PROVIDE Tier 1 scenarios Selection of PROVIDE Tier 2 scenarios with various levels of temperature stabilisation
2	What is the difference between following current trends until 2100 and a 1.5°C-compatible world?	PROVIDE Tier 1 CurPol combined with Ref_1p5 or alternative 1.5°C compatible scenarios such as LD or SP
3	Assuming current policies until 2100, how much can temperatures be reversed until 2300?	PROVIDE Tier 1 CurPol_OS
4	What are the differences in societal risk for similar 1.5°C compatible pathways?	PROVIDE Tier 1 SSP1-1.9, REN, NEG, LD, SP
5	What can be said about the emergence of avoided climate risks in the near-term? What's the range of different climate risks outcomes in 2050 – a timescale relevant for climate adaptation?	PROVIDE Tier 1 CurPol, NEG, SSP1-1.9 (or SP) In addition, a selection of PROVIDE Tier 2 scenarios with varying levels of near-term CH4 mitigation can be used to further explore this question.
6	What are long-term (multi-century) climate outcomes from achieving and sustaining net zero greenhouse gas emissions?	PROVIDE Tier 1 GS_NZGHG, NEG_NZGHG, LD_NZGHG, SP_NZGHG
7	Is climate change fully reversible? To which degree is it, or is it not?	PROVIDE Tier 1 NEG_OS_0
8	How does impact and overshoot reversibility depend on different levels of peak warming?	PROVIDE Tier 1 CurPol_OS_1.5C, ModAct_OS_1.5C, ModAct_OS_1C, Ref_1p5, potentially a further selection of "NZGHG" scenarios or PROVIDE Tier 2 scenarios

5. Reversal of the impact chain

Reversal of GMT/EMISSIONS

Our approach to obtain emissions from temperatures takes part in three stages. Firstly, we calculate the expected temperature quantiles of the Tier 2 scenarios using the FaIR SCM (Smith *et al.*, 2018). Secondly, we convert the quantiled temperature trends of the Tier 2 scenarios using principal component analysis (PCA) components. These lineshapes can be seen in figure 3. This decomposition allows us to express the complete temperature trend as being approximately a linear combination of a few trends times a constant. A good fit to the data for a single quantile is obtained with only four components, and an excellent fit to the data for all quantiles is obtained with five components. Thirdly, we fit a polynomial features regression to find the relationship between the PCAs and the emissions.

This produces good results for Tier 2 scenarios that were left out of the training process, for the quantiles of temperature originally found. However, if the structure of the emissions is not similar to the training data – either non-Tier 2 scenarios, or reinterpreting one quantile of Tier 2 scenario as being another quantile - the results are frequently invalid. Invalid results may include net zero dates in the past, positive long-term emissions (in conflict with the net zero date) or values of the methane response quantile not between 0 and 1. These results are considered unphysical. It produces better results if trained on all different quantiles, even if only the median temperature is actually used – the data improves the calibration. With this setup, the R^2 values above 0.99 for all metrics except methane, which is 0.95. The root mean squared error in the reconstruction relative to standard deviation of the original data is given in table 6 and example reconstructions can be found in figure 4.

Table 6: Root mean squared errors in reconstructing properties of unseen emissions scenarios from their temperature trajectories, divided by the variance in the underlying value.

Value	**root mean squared error / std**
2030 emissions	0.11
Net zero year	0.14
Overshoot	0.04
Methane	0.30

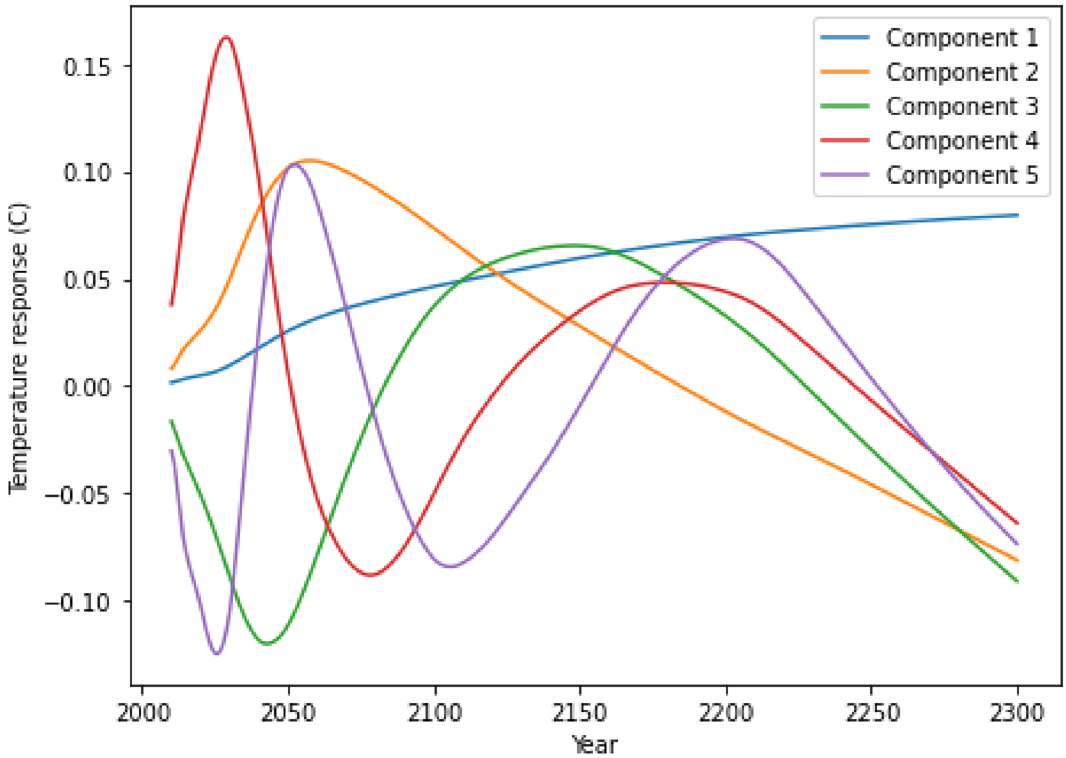

Figure 3: The principal components of the temperature response to the complete set of emissions scenarios at all temperature quantiles. Any temperature trend can be reasonably accurately represented as a linear combination of these.

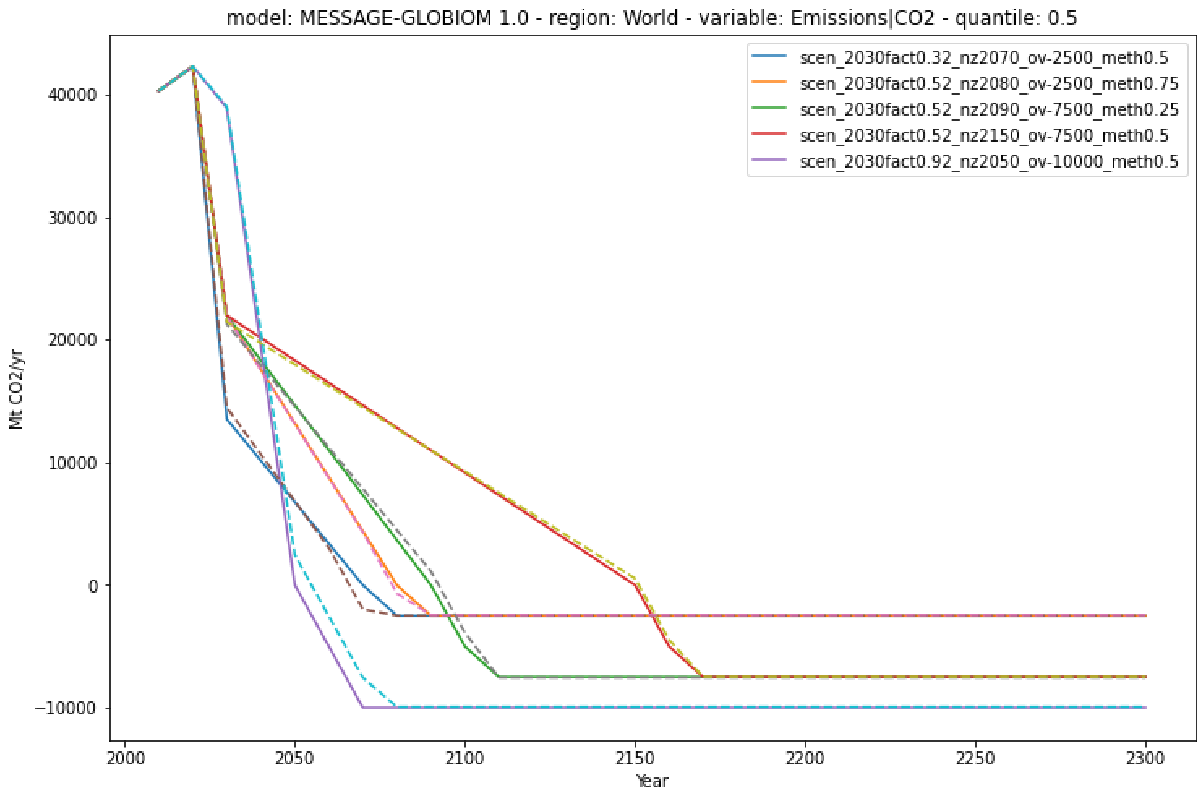

Figure 4: Reconstruction of unseen emissions pathways from PCA of temperature: solid lines are original, dashed are the reconstructions.

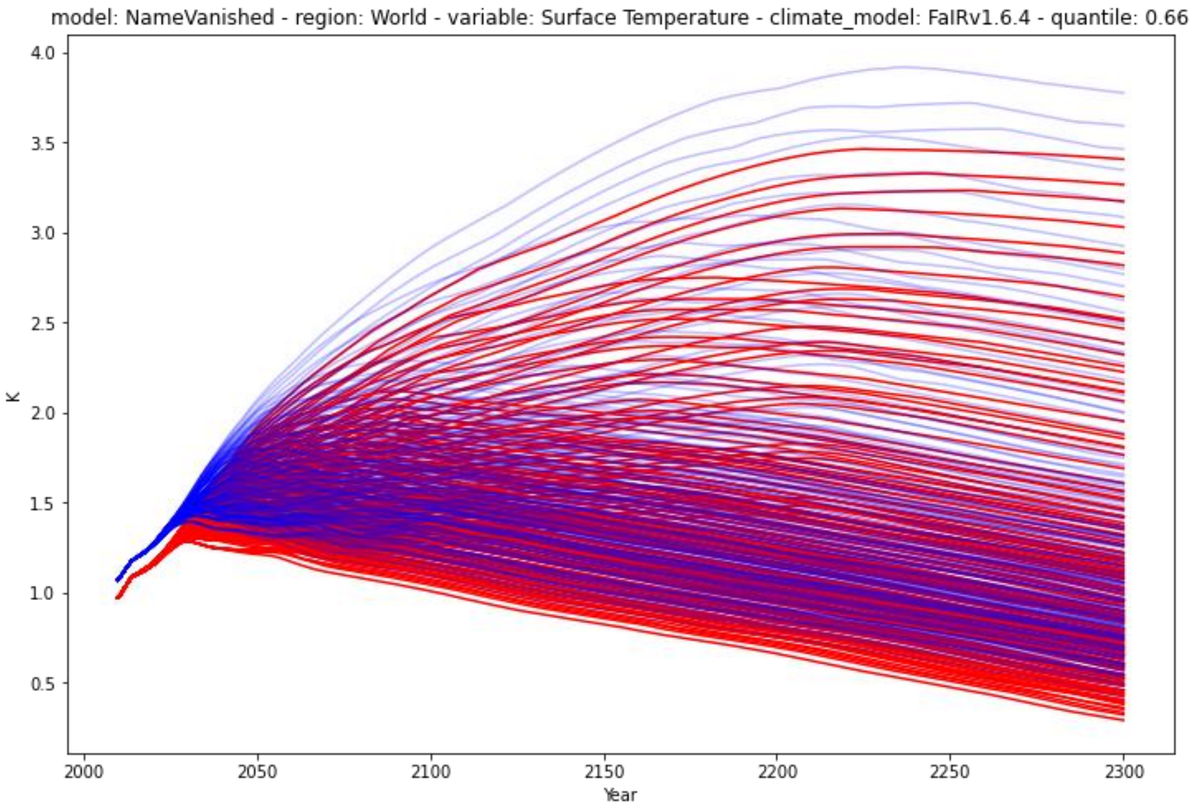

Figure 5: Non-overlapping temperature projections at 0.33 (red) and 0.66 (blue) quantiles at early times make it impossible to find pathways at one quantile that match the temperature trend at another quantile.

6. Annex

Data for the Tier 1 scenarios is taken from the scenario database compiled for the IPCC Sixth Assessment Report (AR6) (Byers *et al.*, 2022) . Scenarios are harmonised to CMIP6 historic data where this is explicitly available. The CMIP6 historical emissions is based on (Velders *et al.*, 2015; Gütschow *et al.*, 2016; Van Marle *et al.*, 2017; Hoesly *et al.*, 2018). We use these values with a multiplicative factor that starts at the value required to unify the data in 2015 to the historic value and tapers to 1 in 2050. Values before 2015 are set equal to the historic value. For emissions where no historic data is available from these sources (i.e., the F-gases), no harmonisation is enacted.

Secondly, we use the module Silicone (Lamboll *et al.*, 2020) to establish relationships between total CO_2 emissions and the other emissions required to run a simple climate model and infill results based on this. For non-F-gas emissions we can infill this using only the SSP2 scenarios in the SR1.5 database. We use the quantile regression technique “quantile rolling windows” (QRW) to find the median level of each species emitted given the level of total CO_2 emissions in a given year. For F-gases, none of these scenarios have a complete set of emissions, so we calculate the total F-gas emissions using this technique, then break down the F-gas total into SF_6, PFCs and HFCs, which are broken down into their components in turn, using any scenarios in the database with the required set of emissions. This takes place using the “decompose collection with time-dependent ratio” function. The MAGICC default set of

historic emissions are appended for all species prior to 2005, which is based on the SR1.5 REMIND-MAgPIE set of emissions.
This set of data is then run through the simple climate model FaIR version 1.6.4 (Smith *et al.*, 2018), as calibrated for AR6. This is a simple model of the climate with range of variables that are constrained to match historic warming since 1765.

The process for Tier 2 scenarios is to take an initial dataseries from the SR1.5 database MESSAGE-GLOBIOM 1.0 model scenario SSP2-4.5, harmonised as above. CO_2 total emissions are linearly extended between 2020 and 2030 to give the scenario's required 2030 emissions ratio, then linearly extended from the 2030 value to 0 in the year of net zero. After that, they decrease towards the overshoot value at a rate not exceeding the maximum CO_2 gradient found in the SR1.5 database, and continue at that level after the decade at which they reach it. The breakdown of total CO_2 into AFOLU and Energy and Industrial (E&I) emissions is done via the Silicone function SplitCollectionWithRemainderEmissions using the SR1.5 database as the comparison, then the other required emissions are infilled using the QRW function. Everything except methane is infilled at the median level conditional on CO_2 total, however the quantile of methane may vary according to another scenario parameter. Emissions of all species except CO_2 are kept constant after 2100. The temperature is calculated using FaIR, as above.

7. Data availability

Scenarios emissions and temperature data are available from Zenodo at https://zenodo.org/record/6833278#.YtBTkXbMJPY.

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