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SUPPLEMENTARY INFORMATION

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COMMENTARY:

The 'best available science' to inform 1.5°C policy choices

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Supplementary Information

Transient climate response to cumulative carbon emissions (TCRE)

The IPCC defined the "Transient Climate Response to cumulative carbon Emissions" (TCRE) as the global mean warming per 1000 PgC and used expert judgement on the available evidence to assess it to be likely between 0.8°C to 2.5°C per 1000 PgC, for cumulative emissions less than about 2000 PgC until the time at which temperatures peak[1]. No distribution for the TCRE was specified.

Based on the TCRE, it is possible to estimate the cumulative CO_2 emissions compatible with a stabilization at a given temperature. The IPCC assumed a normal distribution with a ±1 standard deviation range of 0.8-2.5°C per 1000 PgC. Mathematically, the total carbon-only quota can be expressed as

$$Q^{CO_2}(T,p) = {}^{T}/_{\Phi^{-1}(p,\mu,\sigma)} \qquad \text{(Equation 1)}$$

where T is the temperature threshold (e.g., 2°C), Φ^{-1} is the normal inverse cumulative distribution function, p the probability, μ=(0.8+2.5)/2=1.65 is the assumed mean TCRE, and σ=0.85 is the assumed standard deviation. All values are from the IPCC AR5[1]. Using this distribution and ignoring other radiative forcings, to limit the warming caused by anthropogenic CO_2 emissions to less than 2°C since the period 1861–1880 with a probability of >33%, >50%, and >66%, would require a cumulative budget of less than about 1570PgC, 1210PgC and 1000PgC since 1870[1] (5740GtCO_2, 4440GtCO_2, 3660GtCO_2). Small adjustments to the bounds of the TCRE, can easily increase or decrease the quotas by 200-300GtCO_2 (Supplementary Table 1), emphasising the importance of expert judgement in specifying the range.

One weakness of assuming a normal distribution is that some values lie below zero (2.6%), and avoiding zero will lead to a skew distribution. One alternative is to take a lognormal distribution. The challenge with this is that the likely range of 0.8-2.5°C per 1000 PgC is insufficient to fully specify a lognormal distribution. For demonstration purposes, the parameters of a lognormal distribution were obtained using optimisation with the prior values based on the TCRE distribution parameters (Option 1) and with the median taken as logμ (Option 2) (Supplementary Figure 3). The optimisation ensured that 68.27% of the values fell between 0.8-2.5°C per 1000 PgC (to be consistent with the range used in the IPCC). Recalculating the quota with a lognormal distribution leads to either lower or higher quotas, depending on the particular parameterisation. Depending on the distribution, changes in the quota could be 200-300GtCO_2 (Supplementary Table 2) emphasising the importance of gaining more knowledge on the distribution.

Uncertainty in the remaining quota

The remaining quota, Q, for a given temperature threshold and probability, is the difference between the total CO_2 quota (Equation 1), the non-CO_2 adjustment, past fossil-fuel and industry (FFI) emissions, and land-use change (LUC) emissions[2],

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$$Q(T,p) = [Q^{CO_2}(T,p) - Q^{non-CO_2}(T,p)] - \sum_{t=1870}^{2015}\left(E^{FFI}(t) - E^{LUC}(t)\right) \quad \text{(Equation 2)}$$

Each component has an uncertainty:

- Total CO_2 quota (Q^{CO2}): The probability embeds uncertainties in the climate system and model spread, but does not include structural uncertainties in the distribution. Modifying the TCRE parameters slightly (Supplementary Table 1), changing the distribution to a log-normal (Supplementary Table 2), could change the quota ±250GtCO_2.
- Non-CO_2 adjustment ($Q^{non\text{-}CO2}$): The non-CO_2 adjustment varies depending on the scenario, temperature threshold and probability[3]. Models estimate the non-CO_2 adjusted quota directly[3] (Q^{CO2}-$Q^{non\text{-}CO2}$) and for a 66% chance of 2°C the range is ±300GtCO_2 (based on 76 scenarios), 50% chance 2°C is ±150GtCO_2 (109 scenarios) and 50% chance 1.5°C is ±25GtCO_2 (2 scenarios). The distributions are not symmetric. The confidence in the non-CO_2 adjustment is low, since different temperature and probability combinations have different numbers of scenarios, and the scenarios do not fully explore the range of non-CO_2 pathways for a given CO_2 pathway.
- Historical FFI (E^{FFI}): Historical CO_2 emission have an uncertainty of ±5% to one standard deviation[4], or about 1500±75GtCO_2.
- Historical FFI (E^{LUC}): Historical CO_2 emission have an uncertainty of ±35% to one standard deviation[4], or about 550±190GtCO_2.

When adding the uncertainties in quadrature, the uncertainty on the remaining 2°C quota with a 66% chance is 850±450GtCO_2 (1 standard deviation), 2°C quota with a 50% chance is around 950±350GtCO_2 (1 standard deviation), 1.5°C quota with a 50% and 66% chance is around 200±450GtCO_2 (1 standard deviation). These values are only indicative.

Scenarios used in Figure 1 (main article)

The IPCC allocated scenarios to categories based on their CO_2-eq concentrations in 2100 using the Kyoto GHGs[5]. The CO_2-eq concentration metric refers to the hypothetical concentration of CO_2 that would result in the same instantaneous radiative forcing as the total from all sources, including aerosols. The scenarios with a likely chance of staying below 2°C have a CO_2-eq concentration range of 430-480ppm CO_2-eq.

The 2015 UNEP Emission Gap Report[6] and UNFCCC Intended Nationally Determined Contributions (INDC) Synthesis Report[7] use the probabilistic temperature threshold based on runs with a simple climate model[5]. The advantage of this method is that different probabilities can be chosen (e.g., 50%, 66%), but only about one half of the scenarios assessed in IPCC AR5 have temperature data limiting the diversity of scenarios that can be used.

The scenarios with a likely chance of staying below 2°C differ slightly depending on the method used to select the scenarios. Using the same dataset, the IPCC has 116 scenarios and UNEP 109 scenarios with a likely chance of staying below 2°C.

In Figure 1 in the main paper, we used the 2°C scenarios with a 66% chance of staying below 2°C in 2100 (Supplementary Table 3) used in the UNEP Emissions Gap Report and the UNFCCC INDC Synthesis Report. These particular scenarios ('Delay 2020') assume globally weak policies to 2020, then strong action after 2020. We removed scenarios that differ only in burden sharing[8], as in the UNEP Emissions Gap Report. Since the temperature threshold is in 2100, some scenarios may exceed 2°C before 2100 (last column) and those six scenarios are used in the UNFCCC INDC Synthesis Report.

Supplementary Tables

Supplementary Table 1: The total carbon quotas ($GtCO_2$) for a 33%, 50%, and 66% chance to stay below 2°C showing the differences due to a different range in the TCRE, assuming a normal distribution.

TCRE	Change	33%	50%	66%
0.8-2.5 °C/1000PgC	Default	5740	4440	3660
0.9-2.4 °C/1000PgC	Narrow range	5550	4440	3740
0.7-2.6 °C/1000PgC	Wider range	5950	4440	3590
0.9-2.6 °C/1000PgC	Range up	5330	4190	3490
0.7-2.4 °C/1000PgC	Range down	6230	4730	3860

Supplementary Table 2: The total carbon quotas ($GtCO_2$) for a 33%, 50%, and 66% chance to stay below 2°C showing the differences resulting from different statistical distributions for the TCRE.

	33%	50%	66%
Normal Distribution	5740	4440	3660
Log-Normal (Option 1)	6370	4960	3930
Log-Normal (Option 2)	5430	4290	3440

Supplementary Table 3: The models used in Figure 1 in the main paper. All scenarios are from the LIMITS project[8]. The scenarios include the second commitment period of the Kyoto protocol until 2020 (for selected countries). After 2020, all countries have a globally uniform carbon price. Two variants of the fragmented action until 2020 were considered, a more lenient reference policy (RefPol until 2020) reflecting unconditional Copenhagen pledges or the stringency of current policies and a strengthened version (StrPol until 2020) based on conditional Copenhagen pledges. The long-term target is either 450 or 500ppm CO_2-eq in 2100. The scenarios used in the UNFCCC INDC Synthesis Report[7] do not exceed 2°C before 2100 ('No' in last column).

Model	Scenario	Exceeds 2°C before 2100
GCAM 3.1	LIMITS-RefPol-450	No
GCAM 3.1	LIMITS-RefPol-500	Yes
GCAM 3.1	LIMITS-StrPol-450	No
GCAM 3.1	LIMITS-StrPol-500	No
IMAGE 2.4	LIMITS-RefPol-450	No
IMAGE 2.4	LIMITS-StrPol-450	Yes
MESSAGE V.4	LIMITS-RefPol-450	Yes
MESSAGE V.4	LIMITS-StrPol-450	Yes
REMIND 1.5	LIMITS-RefPol-450	No
REMIND 1.5	LIMITS-StrPol-450	No

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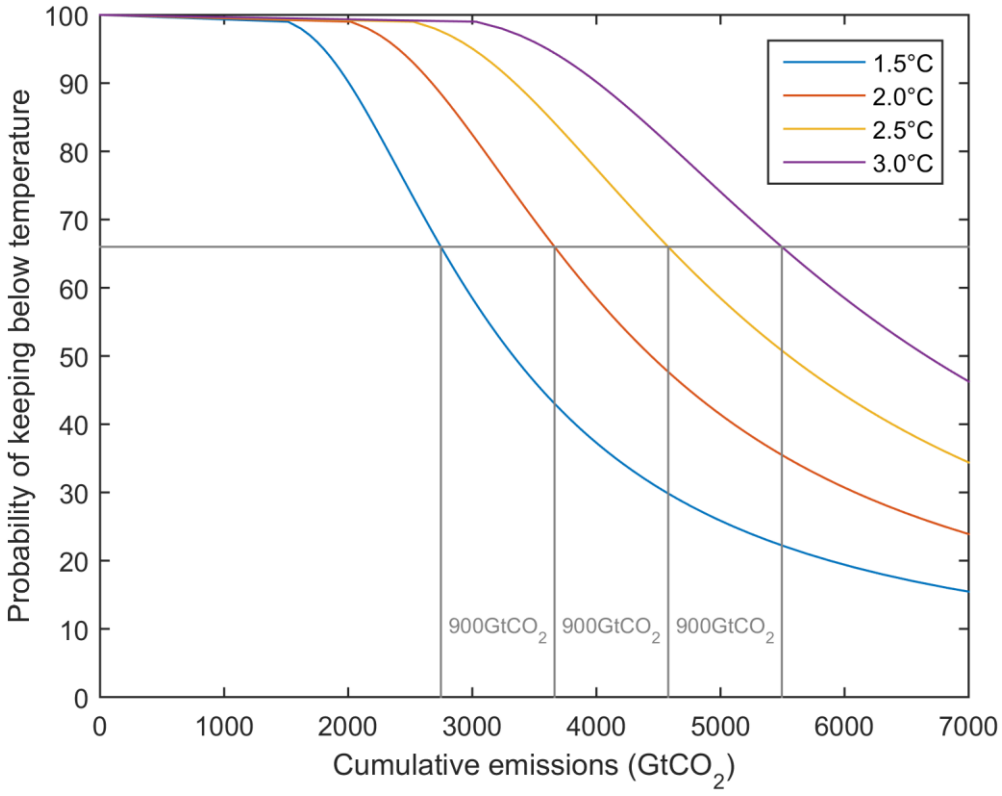
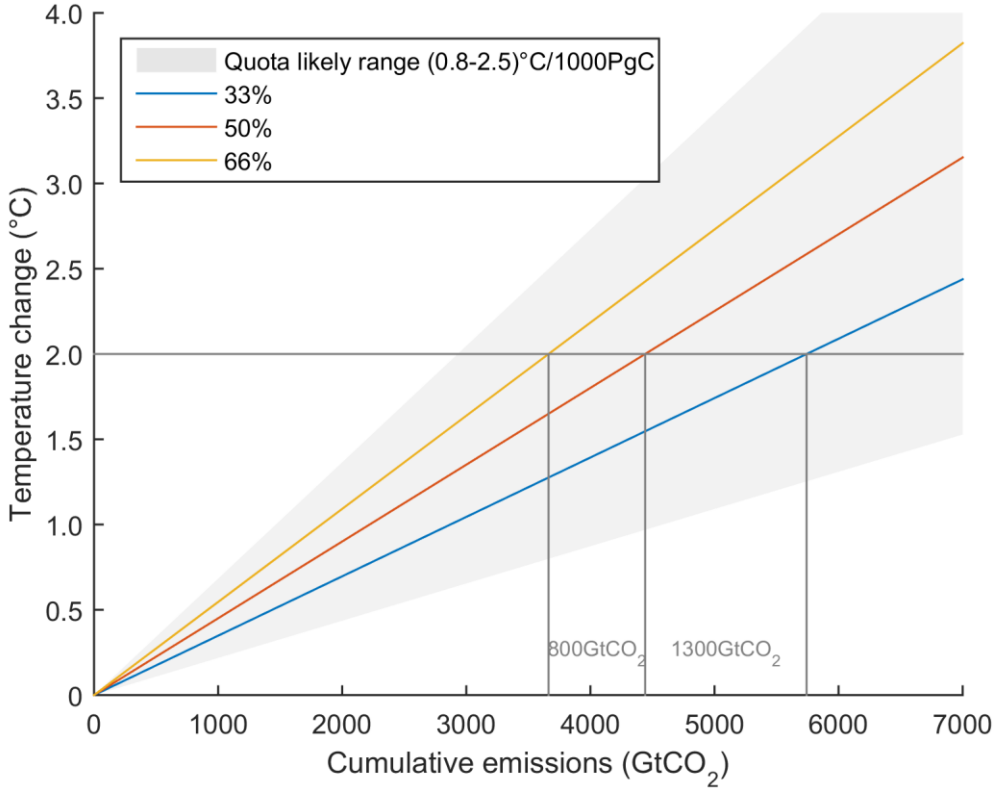
Supplementary Figures



Supplementary Figure 1: The cumulative emissions for given probabilities and temperature increases, Equation (1). For a fixed probability (66%, horizontal line), since the quota is linearly proportional to temperature, then a constant increase in temperature (0.5°C) gives a constant increase in the quota (900GtCO₂).



Supplementary Figure 2: The cumulative emissions for given probabilities and temperature increases, Equation (1). Since the inverse cumulative distribution is non-linear, the quota has a different increase depending on the change in probability.

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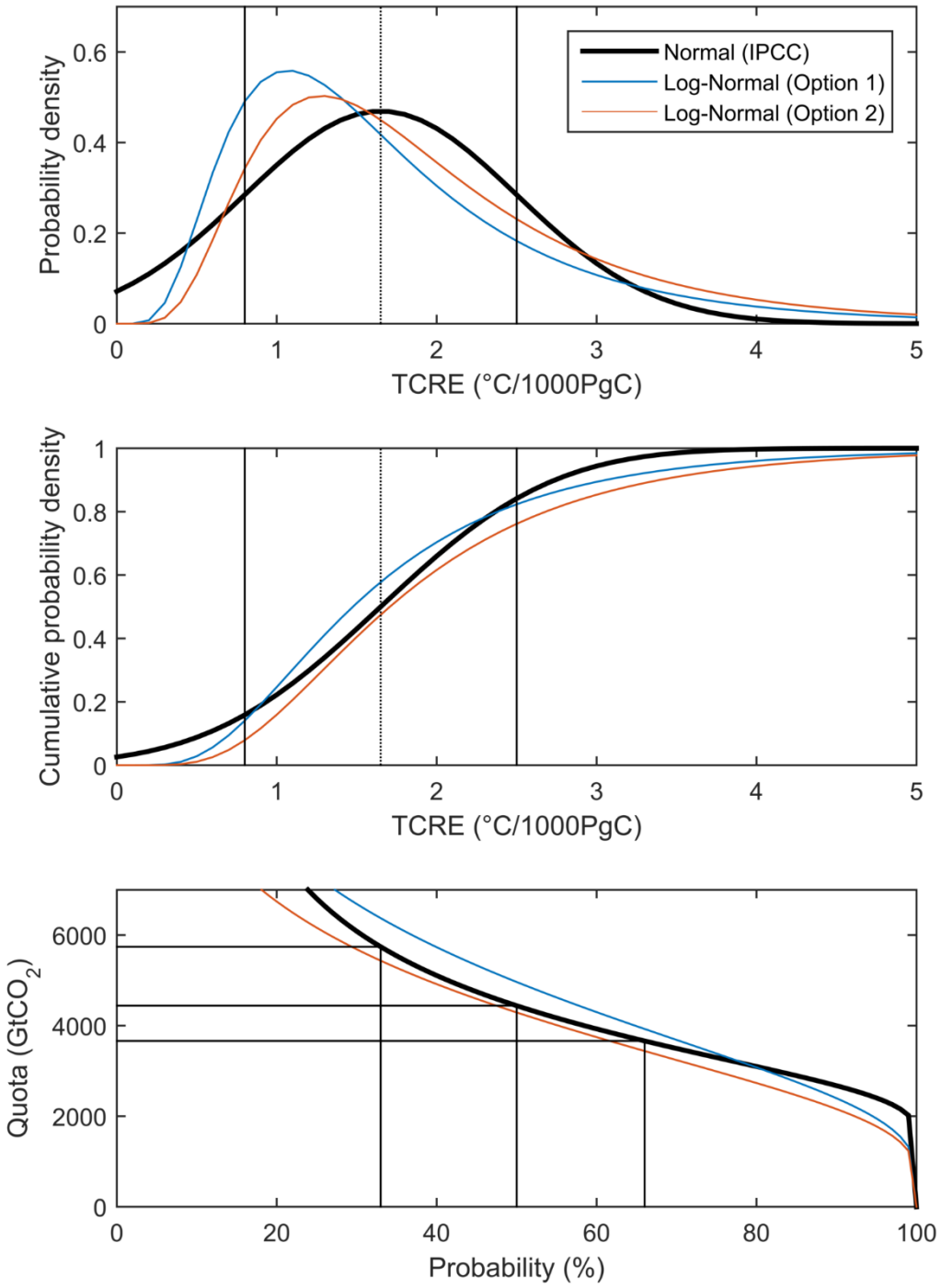
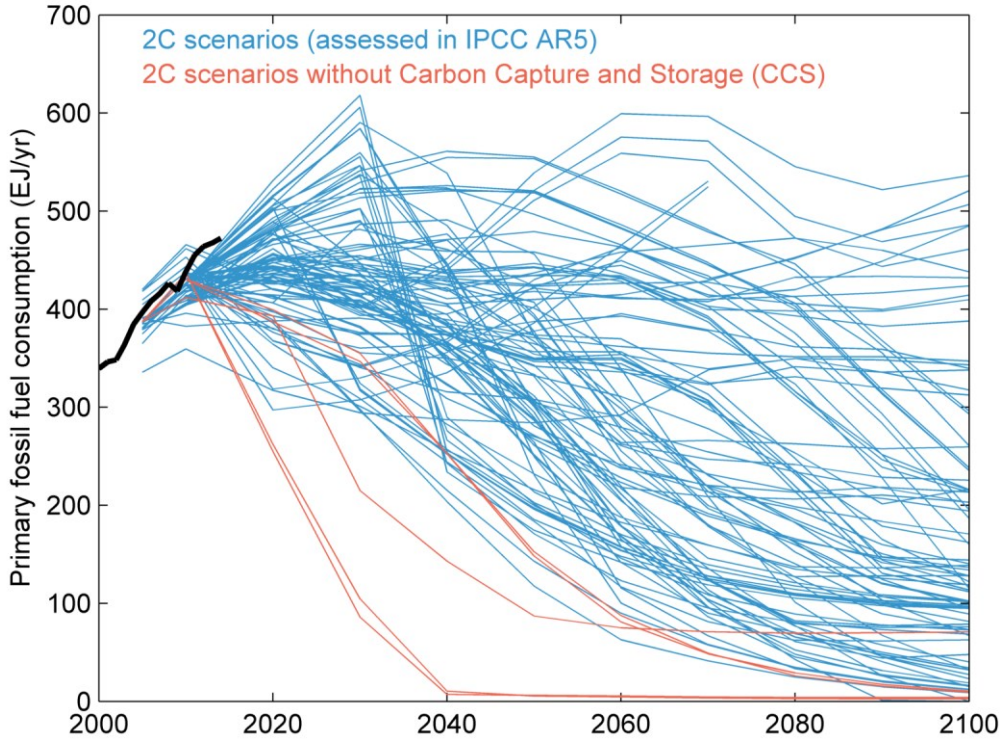


Supplementary Figure 3: The probability (top) and cumulative (middle) distribution functions for the TCRE using a normal and two different lognormal distributions (see text), and the total quota distribution (bottom).



Supplementary Figure 4: The 2°C scenarios assessed by the IPCC AR5, show the primary energy consumption of fossil fuels with and without carbon capture and storage (CCS). Without CCS, there needs to be a radical reduction in the consumption of fossil fuels for a likely chance to keep global average temperatures below 2°C. With CCS, fossil fuel consumption can be maintained at reasonably high levels through to 2100.

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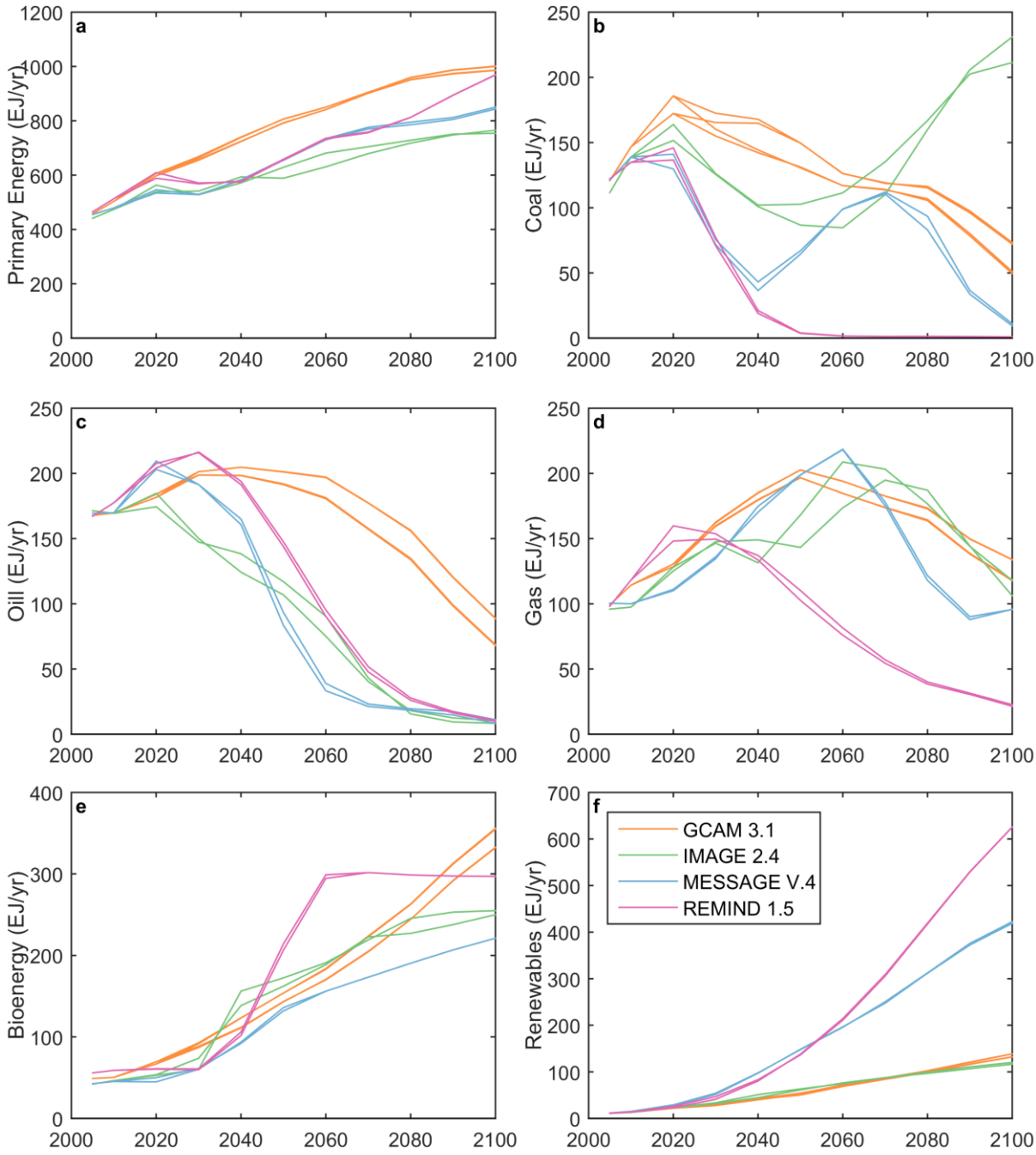

Supplementary Figure 5: The energy consumption in the scenarios used in the UNEP Emissions Gap Report (Figure 1 main article, Supplementary Table 3). ***a****, Energy consumption continues to grow to 2100 in the 'Delay 2020' scenarios.* ***b,c,d****, Fossil fuel consumption can remain high depending on the scenarios and model due to Carbon Capture and Storage (CCS).* ***e****, bioenergy consumption grows to levels where there feasibility is highly debated.* ***f****, renewable energy consumption can reach high levels depending on the scenarios and model, with higher levels of renewable energy consumption leading to lower fossil fuel consumption.*

Supplementary References

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