

Technical appendix

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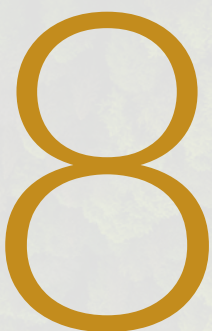
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Technical appendix | Chapter 8

A8.1 Methods

We assess the deployment of carbon dioxide removal (CDR) in pathways relevant to informing the implementation of the Paris Agreement. In this method note, we highlight the scenario set assessed in this report, the definitions of assessed variables and categories of scenarios, and the definitions of the sustainable scenario set.

Scenario set assessed in this report

In this report, we assess the scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC) in the Working Group 3 (WG3) contribution to the 6th Assessment Cycle^{1,2} as well as a selection of scenarios published after this report and available in scenario databases hosted by the International Institute for Applied Systems Analysis (IIASA) as long as they have scenarios with global data. We document the scenario databases we query, the reasons for excluding some, and the relevant references in Table 1.

Table 1: Additional scenario databases queried to compile the scenario dataset assessed in this report.

Database name and link	Reference(where available)	Notes
<i>NGFS Phase 3</i>	-	-
<i>EU Scientific Advisory Board Scenario Database</i>	Ref ^{3,4}	Exclude scenarios that overlap with other assessed databases (e.g., NGFS Phase 3, IPCC AR6 WG3)
<i>GENIE Scenario Explorer</i>	Ref.5 models are increasing the technical representation of novel carbon-dioxide removal (CDR)	-
<i>Climate Solutions Explorer</i>	-	-

Assessment of conventional CDR on land

Different IAMs use different reporting methodologies for CDR on land (via afforestation and reforestation) or do not separate gross emissions and removals in the land sector. To overcome this issue, Gidden et al.⁶ use a compact Earth System Model OSCAR v3.2⁷ to construct a reanalysis dataset using available scenario data from the AR6 WG3 scenarios¹.

¹ The following variables are necessary as a minimum input for this reanalysis: Land Cover|Cropland, Land Cover|Forest, Land Cover|Pasture.

We apply the same methodology from Gidden et al. to the expanded set of scenarios which have the necessary information on land cover (see Footnote 1). We first evaluate the global mean temperature outcomes using the simple carbon cycle and climate model MAGICC v7.5.3⁸⁻¹⁰ using the probabilistic configuration used for the climate assessment in AR6 WG311,12. We then pass on a set of climate assessment variables and the land cover variables to OSCAR v3.2 and use the assessed “direct” (i.e., driven by anthropogenic influence) component of land removals to represent the conventional CDR on land. The climate assessment variables we pass over to OSCARv3.2 are listed below:

- AR6 climate diagnostics|Atmospheric Concentrations|CO₂|MAGICCv7.5.3|50.0th Percentile
- AR6 climate diagnostics|Effective Radiative Forcing|Aerosols|Direct Effect|BC|MAGICCv7.5.3|50.0th Percentile
- AR6 climate diagnostics|Effective Radiative Forcing|Aerosols|Direct Effect|OC|MAGICCv7.5.3|50.0th Percentile
- AR6 climate diagnostics|Effective Radiative Forcing|Aerosols|Direct Effect|Sulfur|MAGICCv7.5.3|50.0th Percentile
- AR6 climate diagnostics|Effective Radiative Forcing|Aerosols|Indirect Effect|MAGICCv7.5.3|50.0th Percentile
- AR6 climate diagnostics|Effective Radiative Forcing|CH₄|MAGICCv7.5.3|50.0th Percentile
- AR6 climate diagnostics|Effective Radiative Forcing|CO₂|MAGICCv7.5.3|50.0th Percentile
- AR6 climate diagnostics|Effective Radiative Forcing|F-Gases|MAGICCv7.5.3|50.0th Percentile
- AR6 climate diagnostics|Effective Radiative Forcing|N₂O|MAGICCv7.5.3|50.0th Percentile
- AR6 climate diagnostics|Effective Radiative Forcing|Ozone|MAGICCv7.5.3|50.0th Percentile
- AR6 climate diagnostics|Effective Radiative Forcing|SF₆|MAGICCv7.5.3|50.0th Percentile
- AR6 climate diagnostics|Surface Temperature (GSAT)|MAGICCv7.5.3|50.0th Percentile

Definitions of CDR in this report

In this report, we evaluate the scenario deployment of two broad categories of CDR: conventional CDR on land and novel CDR. For conventional CDR on land, we use the following variable: AR6 Reanalysis|OSCARv3.2|Carbon Removal|Land|Direct. For novel CDR, we use the following variables: Carbon Sequestration|CCS|Biomass, Carbon Sequestration|Direct Air Capture, Carbon Sequestration|Enhanced Weathering.

Sustainable development – indicators and benchmarks

We categorise the scenario dataset into two categories: (1) scenarios that are relevant to inform the implementation of the Paris Agreement and (2) scenarios relevant to inform the Paris Agreement and meet broader sustainable development objectives. All the scenarios we assess share a common characteristic: they are all relevant to inform the implementation of the Paris Agreement.

Climate (Sustainable Development Goal 13: Climate Action): In line with the previous iteration of this report, we assess three categories of scenarios that are relevant to inform the Paris Agreement, but not all of which are consistent with the climate objectives of the Paris Agreement¹³. These three categories of scenarios correspond to the C1, C2, and C3 categories of pathways assessed by the IPCC^{2,9} – we briefly outline their characteristics below:

- C1 (limit warming to 1.5°C (>50%) with limited overshoot): These scenarios limit peak warming below 1.5°C with a greater than 33% chance and limit end of century warming to 1.5°C with at least a 50% chance. These pathways are arguably most closely aligned with the climate objectives of the Paris Agreement¹⁴.
- C2 (return warming to 1.5°C (>50%) after a high overshoot): These scenarios limit peak warming below 1.5°C with a less than 33% chance and limit end of century warming to 1.5°C with at least a 50% chance.
- C3 (limit warming to 2°C (>67%)): These scenarios limit peak warming below 2°C with a greater than 67% chance.

In addition to this climate-relevant filter, we also use four indicators to capture other sustainable development dimensions. These are by no means a comprehensive attempt to capture all dimensions of sustainable development but should be seen as a relatively pragmatic exercise to identify scenarios that are relatively more aligned with sustainable development objectives.

Population at risk of hunger (Sustainable Development Goal 2): The first indicator we use to evaluate the alignment (or lack thereof) of a scenario with broader sustainable development is the population at risk of hunger (variable: Population|Risk of Hunger). This is an indicator that is computed ex-post using the approach applied by Hasegawa et al.^{15,16} food and ecosystems. Meanwhile, meeting climate goals without global net-negative emissions inevitably needs early and rapid emission reduction measures, which also brings challenges in the near term. Here we identify the implications for land-use and food systems of scenarios that do not depend on land-based CDR technologies. We find that early climate action has multiple benefits and trade-offs, and avoids the need for drastic (mitigation-induced). This approach defines hunger as a state of calorie deprivation lasting over a year – the regional food demand (variable: Food Demand) is assumed to follow a lognormal distribution; the proportion of the population under a minimum dietary energy requirement estimate using the mean value calculated based on historical data is then assessed to provide an indicative assessment of the population at risk of hunger. The corresponding SDG has a target (target 2.1) to end hunger by 2030¹⁷. None of the

pathways we assess meet this target at the global level – we therefore select a benchmark of “relative alignment”, i.e., this indicator should be lower than present day values at the time of global net zero CO₂ in the scenario, noting that total population continues to grow in all scenarios.

Limit bioenergy consumption (Sustainable Development Goal 15): Large-scale deployment of bioenergy is associated with multiple issues relevant to sustainable development. These include competition for land, impacts on food prices and biodiversity, among others¹⁸a bottom-up, systematic, reproducible, and transparent literature assessment of the different options to remove CO₂ from the atmosphere is currently missing. In part 1 of this three-part review on NETs, we assemble a comprehensive set of the relevant literature so far published, focusing on seven technologies: bioenergy with carbon capture and storage (BECCS). We choose global primary energy from biomass (variable: Primary Energy|Biomass) as the indicator and label a scenario as relatively more sustainable if the global value of this indicator is less than 110 EJ at the year of global net zero CO₂ – this differs slightly from the thresholds assessed in previous work (ref.^{18,19}a bottom-up, systematic, reproducible, and transparent literature assessment of the different options to remove CO₂ from the atmosphere is currently missing. In part 1 of this three-part review on NETs, we assemble a comprehensive set of the relevant literature so far published, focusing on seven technologies: bioenergy with carbon capture and storage (BECCS) and corresponds to the level at global net zero CO₂ in the IPCC Illustrative Mitigation Pathway focussed on the achievement of sustainable development objectives²⁰.

Increase afforestation and reforestation (Sustainable Development Goal 15): SDG 15 has a target (Target 15.2) to promote the implementation of sustainable management of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally. We choose the area afforested and reforested (variable: Land Cover|Forest|Afforestation and Reforestation) as the indicator and label a scenario as relatively more sustainable if the indicator is greater than 210 Mha at the year of global net zero CO₂. This value is half the historical value of deforested area²¹. While reforestation tends to promote biodiversity and help restore ecosystems, we note that afforestation can be detrimental in both regards if pursued in unsustainable ways. This analysis is limited to the available information we have from reported scenario outputs, and therefore we use the variable which groups both actions together. Future efforts by the IAM community to separate these two variables is welcome and would support more robust sustainability assessments in the future.

Focus on energy efficiency (Sustainable Development Goal 7 & 12): Energy systems which achieve more sustainable outcomes tend to electrify quickly, reducing the risk of air pollution morbidity, and achieve strong energy efficiency gains to reduce overall primary energy consumption through, for instance, circular economy^{20,22}. Digitisation can reduce energy consumption needs and enhance the capability to attain multiple SDG goals²³. Because scenario data does not report explicitly energy efficiency gains, we use as a proxy total Final Energy consumption, which is the total amount of energy used to provide the provision of services. To give a rough estimate of scenarios with strong energy efficiency and based on scenario evidence² which is consistent with other SDGs, we limit Final Energy

to at least not increase at global net zero CO₂ compared to 2020.

A8.2 Supplementary Data

Scenarios	2030 (Gt CO ₂ e per year [25-75 th percentile])			
	Gross emission reductions from 2020	Total CDR	Conventional CDR	Novel CDR
C1	24 [20, 27]	5.1 [4, 5.7]	4.1 [3.7, 5.1]	0.26 [0.18, 0.47]
C2	12 [4.8, 20]	3.2 [2.8, 4]	3.1 [2.7, 3.8]	0.07 [0.01, 0.23]
C3	12 [3.8, 16]	3.2 [2.7, 4.6]	3.1 [2.6, 4.4]	0.06 [0.01, 0.25]
C1–C3	14 [5.1, 20]	3.5 [2.8, 4.8]	3.3 [2.7, 4.6]	0.11 [0.02, 0.3]
More sustainable scenarios (within C1–C3)	25 [21, 28]	4 [3.9, 4.4]	3.8 [3.7, 4.3]	0.12 [0.05, 0.3]
1.5°C with no novel CDR	29	3.5	3.5	0
1.5°C with higher novel CDR	21	4	3	0.9
1.5°C with higher conventional CDR	19	5.4	5.3	0.1

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