A new scenario resource for integrated 1.5°C climate change research

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Scenarios have been supporting assessments of the Intergovernmental Panel on Climate Change (IPCC) for decades. A new scenario database and a suite of visualisation and analysis tools is now made available alongside the IPCC 1.5°C Special Report to improve transparency and re-use of scenario data across research communities.

Over the past two years, the IPCC has been preparing a Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways[1] (SR1.5). This process was initiated at the explicit invitation of the 193 governments of the United Nations Framework Convention on Climate Change[2] (UNFCCC) as part of the decisions taken in Paris in 2015. During the first week of October in 2018, the resulting report, at more than 200 pages, was presented for approval by the IPCC plenary in Incheon, South Korea. The report assesses the state of scientific knowledge for a large range of 1.5°C-related issues. Amongst these are the required system transitions and options for strengthening the global response to climate change in the context of the sustainable development goals (SDG), including efforts to eradicate poverty and improving health globally.

A new scenario resource

When it comes to assessments of long-term transformations across the energy sector, land-use change and agriculture, and social dimensions, integrated assessment models (IAM) are an essential resource in the scientists' toolbox. IAMs allow to quantify storylines of future development and can, for example, be used to analyse impacts of various policies or the availability of specific technologies on energy system transitions. They capture the coupled energy-land-economy-climate system and describe anthropogenic emissions of GHGs and other forcing agents across sectors and regions over the 21st century. These tools therefore play a unique role in exploring climate change mitigation pathways towards the 1.5°C and 2°C warming limits, and thus provide an important source of literature for SR1.5. In light of many thousands of combined working hours and the large-scale coordinated efforts that go into developing IAMs and producing scenarios it makes sense that they are used to the fullest extent. To this end, the Integrated Assessment Modeling Consortium (IAMC) – the umbrella organization of modelling teams conducting global climate change mitigation analysis – facilitated a coordinated and systematic community effort implemented by IIASA and the IPCC SR1.5 authors. The consolidated scenario data supporting the IPCC SR1.5 assessment has been published online as part of the "*IAMC 1.5°C Scenario Explorer hosted by IIASA*" (https://data.ene.iiasa.ac.at/iamc-1.5c-explorer)[4] *[Note: will go live at time of publication of the report]*), which ensures reproducibility and transparency of scenario assessments, but also allows for the re-use of scenario data by other research communities.

Making data available is consistent with the practices followed by previous IPCC Assessment Reports (e.g., ref. [5] and http://www.ipcc-data.org/). However, this new resource additionally comes with an online "Scenario Explorer" for analysis and visualisation, as well as open-source scientific programming scripts[6] to generate the descriptive statistics and figures included in the SR1.5 that are derived from the scenario database (Fig. 1). This ensures that the scientific statements pertaining to the assessed scenarios can be replicated with moderate effort even by non-experts of numerical modelling. The assessment thereby aims at following the FAIR principles[7] of scientific data and analysis: Findability, Accessibility, Interoperability, and Reusability.

Compilation and consistency

The creation of this new scenario resource was initiated by an open call to the modelling community by the IAMC and IIASA in co-operation with the IPCC. This call invited research teams to submit scenarios that could be relevant to assessing issues related to limiting warming to 1.5°C relative to preindustrial levels, and many modelling teams responded. Cells c-e of Table 1 provide an overview of the research teams that dedicated time and resources to contribute their scenario data to the database.

Scenarios were submitted from a diverse set of recent publications including multi-model comparison projects (e.g., refs [8,9]) and single-model scenario studies (e.g., refs [10,11]).

However, developing a useable scenario database requires more than simply porting diverse data from various sources into one large container. Rather than compiling data directly from the published literature, a central curated database was developed with dedicated contributions from across the integrated-assessment community. This approach aimed at providing a coherent scenario ensemble with a high degree of internal consistency. A common terminology and coherent nomenclature was applied across all submissions, facilitating the computation of ranges for variables and indicators of interest without further need for harmonization or data processing (see Table 1a for an overview of the variable classes that have been included). Furthermore, a number of validation steps as well as bilateral communication with submitting modelling teams to clarify issues ensured that any data that is assessed is shown correctly, and hence interpreted accurately in the SR1.5 report (Fig. 1).

User guidance

This new scenario resource provides a great opportunity for further research and analysis by the wider community. However, some caution is warranted when using scenario ensembles for further analysis.

Importantly, the available collection of scenarios is an 'ensemble of opportunity', the lowest common denominator being that they have been made available to the SR1.5 assessment through submission to the scenario database and have passed a number of validation steps for consistency, completeness and near-term plausibility. The studies underlying these scenarios address issues related to climate change mitigation pathways consistent with 1.5°C of global warming or provide relevant context to the assessment of such pathways; and several of the studies were initiated with the aim to feed into the SR1.5 assessment process. However, each study may address a different set of research questions, and the scenario designs as well as underlying assumptions are hence expected to differ in ways that may affect the characteristics of resulting pathways. Examples of such assumptions are the availability or speed of deployment of carbon dioxide removal (CDR), which includes bio-energy with carbon capture and sequestration (BECCS). One guiding principle when using an unstructured scenario ensemble (i.e., consisting of scenarios that were not developed based on a structured set of variations) is hence that in most cases it is incorrect to consider a scenario ensemble as a statistical sample that provides any information in terms of likelihood or agreement in the literature. Additional "do's and don'ts" for conducting an assessment of unstructured scenario ensembles are elaborated in more detail in Box 1.

One way of assessing characteristics of scenarios consistent with a specific temperature level is to group available scenarios based on their temperature outcome with the help of a reduced-complexity carbon-cycle and climate model[12]. The ranges across the scenarios within each group inform the spectrum of outcomes currently available in the literature for each warming category in terms of greenhouse gas emissions, speed of the energy system transition, and the deployment of CDR technologies, amongst other indicators. The lower panel of Figure 1 illustrates the various types of information available and how the numerical results can be used to quantify narratives of mitigation action: several driving trends like economic growth and total population are leading to changes in energy demand, which in turn impact emissions from the energy sector. It also illustrates how limiting global warming to 1.5°C by 2100 can be achieved in a variety of ways, for example by large-scale deployment of CDR measures like BECCS or a very fast phase-out of fossil fuels and low energy demand, or any combination of these options. However, as indicated earlier, the number of available scenarios with a specific characteristic does not correlate with the likelihood of such a scenario.

An invitation to re-use

The public release of the database and the analysis notebooks for the SR1.5 is intended to increase openness and transparency towards the scientific community working on integrated assessment and climate change mitigation policies as well as towards the public at large[13]. The present scenario ensemble can also serve as a starting point for a similar community effort going into the Sixth Assessment Report of the IPCC. The scenario data and the open-source analysis tools allow the community to better link domain-specific knowledge to the wider policy discussion by providing the flexibility to analyse sector-specific indicators that may be of interest to particular communities. For example, the climate finance community could use these scenarios to better understand investment needs towards the required system transformation; land-use change projections could inform assessment of biodiversity risks; and insights on mitigation options at the global scale and their variations can feed into discussions at the national or local level. Such a re-use across disciplines of scenario data originally developed by the IAM community could further broaden and facilitate the ongoing discourse about societal priorities including climate change mitigation and sustainable development.

a. Classes of variables: - Energy system configuration and fuel mix - Emissions by species and sectors - Carbon dioxide removal (CDR) including carbon capture and sequestration (CCS) - Investment expenditure - Socioeconomic indicators (population, GDP development, prices) - Land use and agricultural production - Indicators for sustainable development	**b. Types of scenarios:** - Baseline or no-policy scenarios (as reference) - Constraints on cumulative emissions until 2100 - Implementations of the Nationally Determined Contributions (NDC) - Stringent short-term policy implementations (e.g., transport sector, energy efficiency) - Limited availability of specific technologies - Combinations of the above
c. Modelling frameworks: - AIM - C-ROADS - GENeSYS-MOD - GCAM - IEA ETP Model - IEA World Energy Model - IMAGE - MERGE - MESSAGEix-GLOBIOM - POLES - REMIND-MAgPIE - Shell World Energy Model - WITCH	**d. Model inter-comparison studies** - Quantifications of the shared socioeconomic pathways (SSP) for various forcing levels: Riahi et al. (2017), Rogelj et al. (2018) - ADVANCE: Vrontisi et al. (2018), Luderer et al. (2018) - CD-LINKS: McCollum et al. (2018) - EMF-33: Bauer et al. (2018)
f. Pathway classes by warming impact: - Below 1.5°C 9 - 1.5°C return with low overshoot 44 - 1.5°C return with high overshoot 37 - Lower 2°C 74 - Higher 2°C 58 - Above 2°C 189 - Not categorized by warming impact 3 Total number of assessed scenarios 414	**e. Single-model studies**: - Bertram et al. (2018) - Grubler et al. (2018) - Holz et al. (2018) - Kriegler et al. (2018) - Liu et al. (2017) - Löffler et al. (2017) - Luderer et al. (2013) - Marcucci et al. (2017) - OECD (2017) - OECD/IEA and IRENA (2017) - Rogelj et al. (2013a, 2013b, 2015) - Shell International B.V. (2018) - Strefler et al. (2018) - van Vuuren et al. (2018) - Zhang et al. (2018)

Table 1 | Overview of scenario ensemble Classes of variables, types of scenarios, list of modelling frameworks and underlying literature of the scenarios submitted, and number of scenarios per assessed warming category

The "Do's and don'ts" for analysing ensembles of opportunity of IAM scenarios:

In this context, an 'ensemble of opportunity' refers to a serendipitous collection of scenario data from a variety of sources and studies. We here provide a list of do's and don'ts for analysing such ensembles, as well as some examples.

1) **Don't interpret the scenario ensemble as a statistical sample or in terms of likelihood/agreement in the literature.** A number of scenarios show that limiting global warming to 1.5°C can be achieved without deployment of bioenergy with carbon capture and sequestration (BECCS), while the majority of scenarios use it (cf. Figure 1c). This information by itself does not imply that reaching ambitious climate goals is less likely without BECCS – instead, it shows that pathways with and without BECCS exist for implementing the Paris agreement, highlighting that different societal preferences and strategies can result in vastly different outcomes.
2) **Don't focus only on the medians, but consider the full range over the scenario set**. While it is often easier to communicate single numbers rather than ranges, the full breadth of indicators or trajectories within a scenario set carries important information about the available options (cf. Figure 1a).
3) **Don't cherry-pick individual scenarios to make general conclusions**. Select an appropriate subset of scenarios instead, in such a way that differences or alternative developments between scenarios within one category can be highlighted (cf. Figure 1d).
4) **Don't over-interpret scenario results and do not venture too far from the original research focus.** All scenarios in this compilation analyse the emission pathways and the energy system transformation in mitigation pathways; therefore, comparing emissions and similar indicators is a valid meta-analysis. In contrast, most scenario designs implicitly optimize global welfare (e.g., they often look for the least cost solution with respect to mitigation efforts) and are not designed to consider inter-regional fairness or burden-sharing methods. Therefore, regional GDP changes under mitigation policies from these scenarios provide little information about who will ultimately "win or lose from climate action" and is taking the meta-analysis outside of the application domain of these scenarios.
5) **Don't conclude that the absence of a particular scenario (necessarily) means that this scenario is not feasible or possible.** The solution space in an 'ensemble of opportunity' is not comprehensive. Scenarios might be "missing" because no study asked a research question that would require such a scenario to be developed, or, even more banal, because such a scenario was published in the literature but not included in the ensemble for other reasons. Unavailable scenarios do not preclude them from being possible, unless a study specifically indicates that a particular scenario was attempted but could not be produced by a modelling framework (e.g., limiting radiative forcing in 2100 to 1.9W/m^2 under SSP3 socioeconomic assumptions, cf. ref [1,3]).

Box 1 | A user's guide to the analysis and interpretation of scenario ensembles

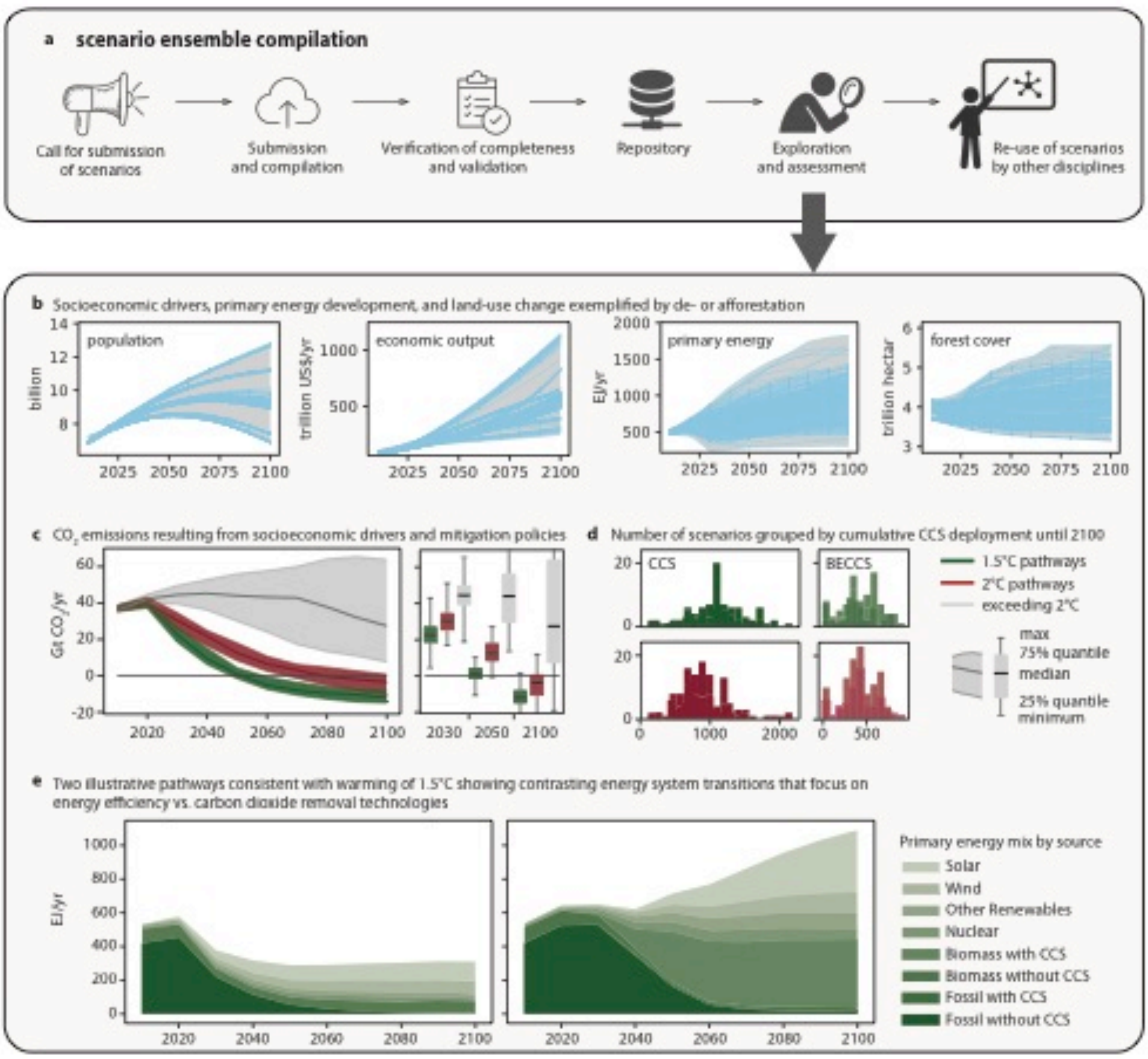

Figure 1 | Overview of process of compilation of IAM scenario data, and illustrative data visualisations. a. Process of creating, vetting, analysing, and distributing IAM scenario data; b-e, illustrative data analysis of information available in the new scenario resource. Overview of range of socioeconomic drivers, primary energy and forest cover (panel b), global CO_2 emissions for scenario subsets consistent with 1.5°C or 2°C (panel c) as well as the distribution of CCS and BECCS deployment across these subsets (panel d); evolution of primary energy contributions in two illustrative, very different 1.5°C pathways[3,10]. Icons in panel a are licensed under a Creative Commons License by LeftHandedGraphic, TukTuk Design, Luis Prado, joeartcon, Kimmi Studio, and Creative Stall at TheNounProject.

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Author Contributions

DH and KR coordinated the development of the scenario resource. All authors contributed to the development of the scenario resource. DH and JR wrote the first draft of the manuscript, with contributions from all authors. DH created the figure, with inputs and suggestions from all authors.

Competing Interests statement

The authors declare no competing interests.

References

1 IPCC. *Special Report on Global Warming of 1.5°C (SR1.5).* (Intergovernmental Panel on Climate Change, 2018).
2 UNFCCC. *Adoption of the Paris Agreement FCCC/CP/2015/10/Add.1.* (2015).
3 Rogelj, J. *et al.* Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change* **8**, 325-332, doi:10.1038/s41558-018-0091-3 (2018).
4 Huppmann, D. & et al. (Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis, 2018).
5 Krey, V. *et al.* in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx) (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014).
6 Huppmann, D. (2018).
7 Wilkinson, M. D. *et al.* The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data* **3**, 160018, doi:10.1038/sdata.2016.18 (2016).
8 Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* **42**, 153-168, doi:10.1016/j.gloenvcha.2016.05.009 (2017).

9 McCollum, D. *et al.* Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy*, doi:10.1038/s41560-018-0179-z (2018).
10 Grubler, A. *et al.* A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy* **3**, 515-527, doi:10.1038/s41560-018-0172-6 (2018).
11 Kriegler, E. *et al.* Short term policies to keep the door open for Paris climate goals. *Environmental Research Letters*, doi:10.1038/s41558-018-0119-8 (2018).
12 Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmos. Chem. Phys.* **11**, 1417-1456, doi:10.5194/acp-11-1417-2011 (2011).
13 Pfenninger, S. Energy scientists must show their workings. *Nature* **542**, 393, doi:10.1038/542393a (2017).