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Using large ensembles of climate change mitigation scenarios for robust insights

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As they gain new users, climate change mitigation scenarios are playing an increasing role in transitions to net zero. One promising practice is the analysis of scenario ensembles. Here we argue that this practice has the potential to bring new and more robust insights compared with the use of single scenarios. However, several important aspects have to be addressed. We identify key methodological challenges and the existing methods and applications that have been or can be used to address these challenges within a three-step approach: (1) pre-processing the ensemble; (2) selecting a few scenarios or analysing the full ensemble; and (3) providing users with efficient access to the information.

The past two decades have seen an explosion of climate change mitigation scenarios (Fig. 1) emanating from different disciplinary communities, including energy, land use and integrated assessment modelling[1–5]. This dynamic led to collections of scenarios being gathered in publicly available databases[3,6]. The upcoming IPCC Sixth Assessment Report databases of global and national mitigation scenarios are likely to be larger than previous databases and novel in their inclusion of national climate–energy scenarios.

In parallel, mitigation scenarios are progressively gaining new users and new uses[7,8]. Well-established uses by governments for climate policy design and by non-governmental organizations for advocacy are spreading to other countries. A new use case is the use by local governments and private companies to assess the alignment of policies and strategies with science-based targets[9]. Another example is the assessment of climate-related financial risks and opportunities for corporations, financial institutions, central banks and financial regulators[10,11].

The conjunction of this rapid expansion of mitigation scenarios being produced and the emergence of new scenario users creates a critical opportunity for the extended use of ensembles of scenarios. An ensemble of mitigation scenarios is a collection of a large number (from dozens to thousands) of emissions and socioeconomic scenarios computed with a variety of modelling frameworks that represent systems with comparable boundaries (Box 1). While a large body of literature has analysed and criticized scenarios and their uses[8,12–14], the specific uses of scenario ensembles have received relatively little emphasis. This Perspective aims at bridging this gap, and points to notable examples of scenario ensemble uses.

We argue that the more extended use of scenario ensembles has the potential to bring new and more robust insights, and to better serve the needs of the final users of information based on climate mitigation pathways, especially in the context of decision-making under uncertain conditions. This Perspective takes stock of scenario ensembles' uses and their limitations. It identifies key methodological issues, available approaches to address them and points out development needs.

Potential and challenges of using scenario ensembles

Scenario ensembles have been used within IPCC processes since the early days to gather and assess the existing knowledge to provide emission pathways for climate modelling[15,16], to inform target and climate policy formulation[4,17–19], and to compare alternative mitigation pathways[20]. Compared with the production or use of a limited number of scenarios, scenario ensembles bring three potential advantages that are illustrated with specific cases in Table 1. They also raise challenges that differ from those related to the use of single scenarios.

First, ensembles may better capture uncertainties, and thus lead to them eventually being better considered in decision-making processes to design robust strategies. This has been applied recently in a risk assessment context by stakeholders in the finance sector (Table 1, illustrative case 1). Ensembles may indeed represent the diversity of assumptions, worldviews or modelling frameworks, which reflects technological, socioeconomic or epistemic uncertainties. In addition, methods developed to guide decision-making under deep uncertainties[21] can be applied to mitigation scenario ensembles. These techniques are adapted to decision contexts where there is no agreement on (1) proper models to represent the system at stake, (2) probabilities of key input parameters and (3) how to value the desirability of alternative outcomes[22]. They help decision-makers to understand the vulnerabilities of the

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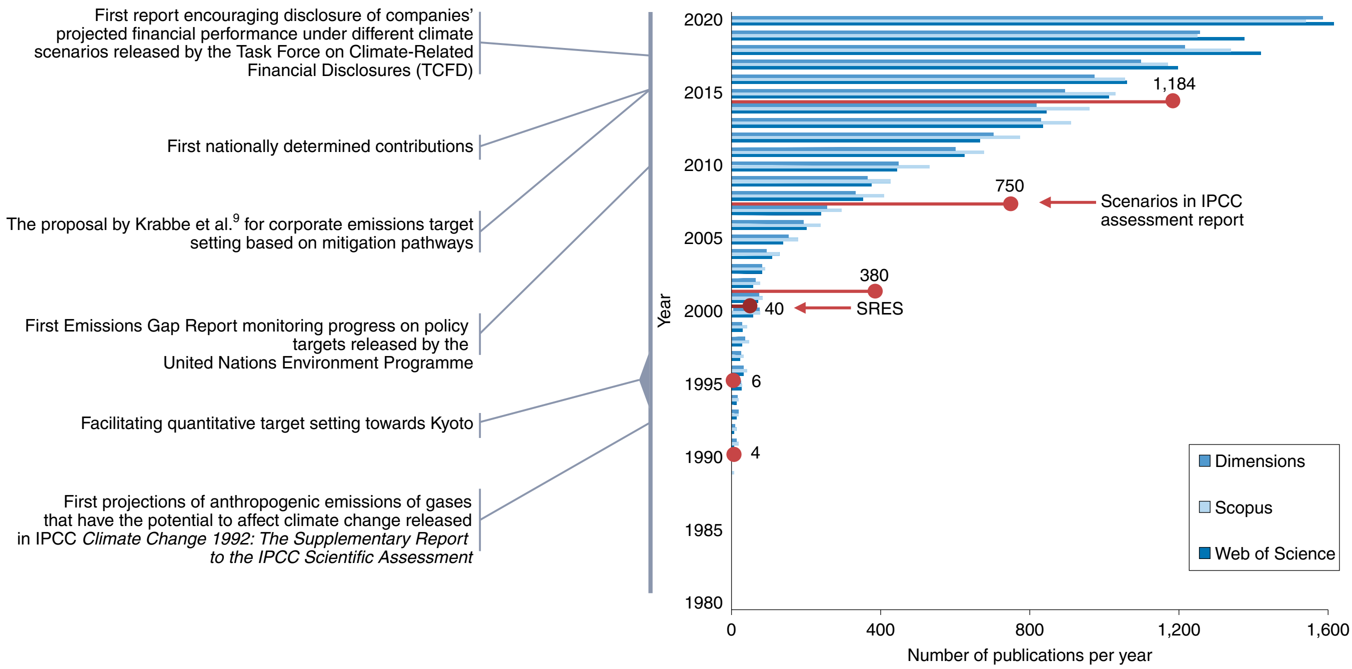

Fig. 1 | Overview of climate change mitigation scenarios and the diversification of their uses and users. The bar chart shows the evolution over time (1980–2020) in the number of publications corresponding to the keywords 'climate change mitigation scenarios' in three databases (Web of Science, Scopus and Dimensions; shown in blue) and in the number of scenarios collected in the databases of emissions and mitigation scenarios associated with the IPCC assessment reports (in red). A chronology of key developments illustrates the evolution in scenario uses.

proposed strategies and to identify the trade-offs among the potential responses. While examples of such uses of mitigation scenarios are relatively rare[23–26], there is potential for the use of these techniques in the deeply uncertain context of mitigation.

Second, the use of ensembles may increase the salience, credibility and legitimacy of the information produced[27]. This motivated their use in the context of assessing the alignment of short-term targets with the Paris Agreement objectives[4] (Table 1, illustrative case 2). Salience, which refers to the relevance of this information to the needs of users, can be increased if users can extract, from existing knowledge, information tailored for their specific needs, for example, through meta-analyses or the identification of relevant scenario subsets according to their criteria. At the same time, analysts have to ensure the usability and interpretability of information, as ensembles embody a multitude of scenarios that vary across variables, input assumptions and underlying models. Credibility, which involves 'the scientific adequacy of the technical evidence and arguments'[27], can be increased by including large amounts of knowledge, implementing systematic approaches or revealing the uncertainties and making them visible in the process. Legitimacy, which reflects the perception of how fairly diverging perspectives are considered in the generation of scenarios, may be improved by the use of scenario ensembles as they may reflect diverse (and even diverging) approaches, worldviews and assumptions. If care is not taken, however, the analysis can face critical transparency issues, due to the large amount of information involved in the process.

Third, the use of ensembles is a way of building a comprehensive or representative picture of the knowledge produced by modellers. This is necessary, for example, for analysts who want to assess modelling practices, as exemplified by illustrative case 3 in Table 1. The criteria of representativeness or comprehensiveness are indeed critical to produce a well-founded and authoritative analysis. The challenge may then be to concretely implement this quest for exhaustiveness when the scenarios are produced by a wide variety

Box 1 | Scenario ensembles can be 'structured' or 'unstructured'

Ensembles are sets of scenarios that represent systems with comparable boundaries and share harmonized definitions on variables. Scenario ensembles can be 'structured ensembles', constructed from a systematic design (Fig. 3). With a single model, the design varies the model input parameters, following a Monte Carlo scheme[100,101], or adopts a systematic combination of discrete sets of variables[23,102] to explore parametric and socio-economic uncertainties. With multiple models, model intercomparison projects explore structural model uncertainty, behaviour and specificities among a few scenarios with harmonized assumptions for key parameters.

Scenario ensembles can conversely be 'unstructured ensembles', with scenarios gathered from various sources. A prominent example is the IPCC's databases of scenarios, including the IAMC 1.5°C Scenario ensemble[90]. In that case, the process to gather scenarios was a community effort to facilitate and coordinate modelling teams voluntarily submitting their available scenarios to a curated database. Another method to construct an unstructured ensemble is to systematically collect scenarios corresponding to queries searched in publications databases, as in ref. [29].

Although scenario ensembles are designed to explore the possibility space, neither type of ensemble can be interpreted as a perfect statistical sample. Given the unknown unknowns[6], the scenarios' outcomes cannot be interpreted in terms of likelihoods, and even large scenario ensembles do not fully or equally explore the space of possibilities[85].

Given the above challenges, and the risk of scenarios being mishandled, the next section lays out a three-step approach for preparing and using ensembles of mitigation scenarios.

Table 1 | Illustrative cases of uses of climate mitigation ensembles

	Illustrative case 1	Illustrative case 2	Illustrative case 3
Reference	Network for Greening the Financial System *NGFS Climate Scenarios for Central Banks and Supervisors* (2021)[10].	Roelfsema, M. et al. Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nat. Commun.* **11**, 2096 (2020)[4].	Jaxa-Rozen, M. & Trutnevyte, E. Sources of uncertainty in long-term global scenarios of solar photovoltaic technology. *Nat. Clim. Change* **11**, 266–273 (2021)[29].
Typical end-users of the information produced	Stakeholders in the finance sector.	Policymakers, United Nations Framework Convention on Climate Change process stakeholders, investors, general public.	Climate mitigation modellers, knowledge reviewers.
Objective of the study	Select a set of transition scenarios to perform stress tests to assess the stability of the finance system under contrasting climate policy alternatives.	Assess the alignment of short-term stated targets (from governments in the specific example here, but can also be applied to corporate targets) with pathways compatible with long-term climate goals.	Assess the sources of uncertainty in solar photovoltaic development in mitigation pathways and compare pathways from integrated assessment models with results from other modelling approaches.
Value in using an ensemble	The ensemble captures a large spectrum of possible futures, which reflect technological, socioeconomic and epistemic uncertainties. It allows users to explore the robustness or vulnerability of financial actors to these uncertainties.	A credible and legitimate 'corridor' of pathways compatible with the long-term objectives can be extracted from the ensemble to serve as a point of comparison because the ensemble captures a large spectrum of possible futures and is supported by well-established models that consider diverse worldviews and assumptions.	The ensemble allows users to assess the practices of the modelling community by considering its whole production when examining model results and assumptions.

See Supplementary Information for an extended version.

of actors and communicated in many arenas, or to prove the representativeness of a selected sample of pathways.

Three key steps for using ensembles

Three main actor groups are typically involved in the use of an ensemble of scenarios. First, end-users, such as governments, commission the investigation of a policy or strategy question. Second, analysts derive relevant knowledge from various sources, including scenario ensembles. Third, modellers develop and provide the scenario ensembles. The workstream is not necessarily coordinated and integrated from start to end. When the study involves well-identified end-users for the knowledge to be produced, engagement between the analysts and end-users is necessary to refine the study objective. Given the range of new users, and the potential novelty and complexity of scenario ensembles, this engagement is crucial for understanding and adjusting to users' needs. It may involve tailoring the choice of scenario ensembles and analytical methods to the question at hand, or co-producing the analysis with users[10,28].

We propose here three steps to guide analysts in the use of ensembles of climate change mitigation scenarios (Fig. 2). 'Pre-processing the ensemble' is the preliminary step and 'Providing users with efficient access to the information' comes at the end of the process. Two paths, either 'Selecting scenarios from the ensemble' or 'Exploring the full scenario ensemble', form the core of the analysis. In the following sections, we will highlight, for each step, key methodological issues, existing methods and applications to address them, as well as future developments that are still needed.

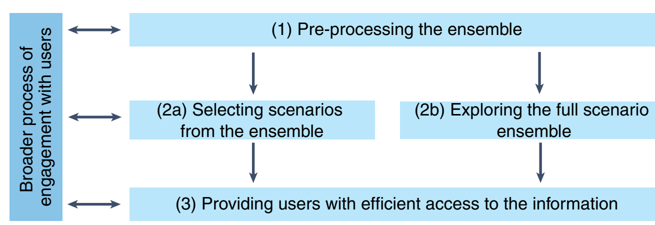

Fig. 2 | Steps to use ensembles of scenarios. Flow chart illustrating the three key steps.

Pre-processing the scenario ensemble

Once the purpose of the study has been defined, the analysts assemble scenarios into an ensemble or select an existing full scenario database (block 1 in Fig. 3). To create an ensemble, the analyst may, for example, collect scenarios from publications with systematic search techniques[29], call for scenario submissions from modelling teams or run scenarios if access to a model is granted. These approaches can also serve to complement an existing scenario database in which necessary scenarios, or variables, are missing. In-filling techniques can further complement scenarios with missing variables[30].

Then, quality control and vetting are necessary to improve the credibility of the information produced (block 2 in Fig. 3). This requires screening scenarios on the basis of quality criteria and fitness for the purpose of the study. Some scenarios may contain errors (for example, impossible signs or orders of magnitude for some variables) or may not match historical data for socioeconomic, technological or policy trends. In addition, exclusion criteria may also pertain to the purpose of study. For example, for studies analysing the implications of coal phase-out, scenarios where substantial coal use is retained should be excluded. In this process of judging the appropriateness of the ensemble for the intended use, the analyst should ponder the tension between excluding scenarios that are judged 'inappropriate' and missing some low-probability high-risk types of scenario or those that represent future discontinuities. These two issues are critical for uses that seek to analyse risks and study the robustness, or vulnerabilities, of strategies and policies.

Such quality control and vetting processes have been adopted by the modelling community and are common in knowledge assessment processes. For example, for the IPCC's *Special Report on Global Warming of 1.5 °C* (SR1.5), the criteria to retain scenarios combined a quality assessment of the scenarios (validity assessment of 2010 emissions for aggregate Kyoto GHGs, consistency with historical energy balances, plausibility assessment of near-term development: no negative emissions from land use in 2020) with some necessary characteristics of the scenarios to assess temperature

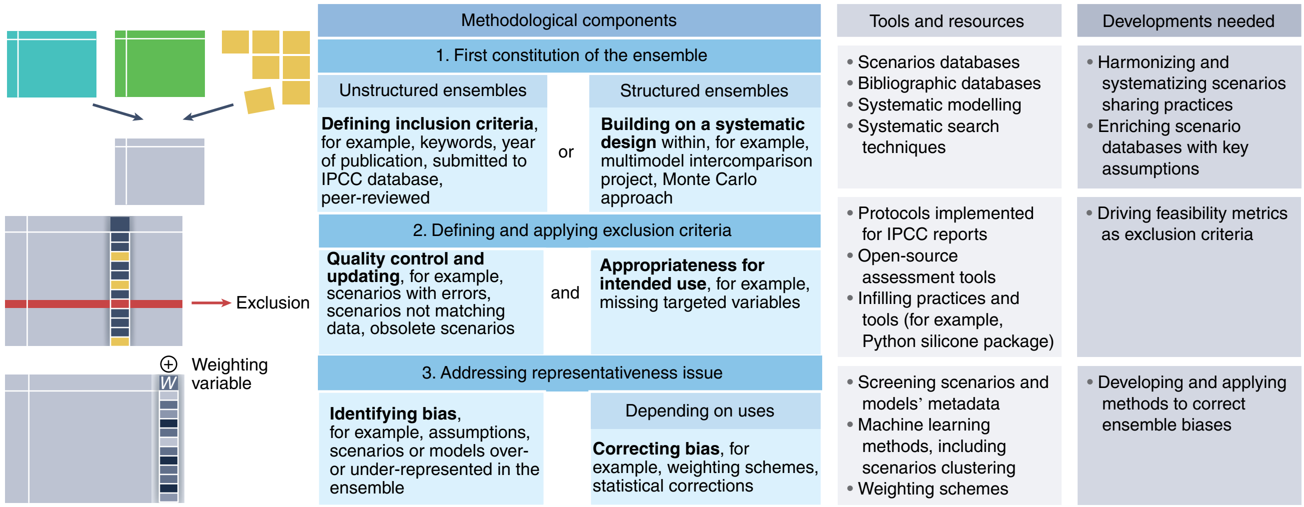

Fig. 3 | Methodological components to compile and pre-process scenario ensembles. The figure summarizes the existing tools and resources, as well as developments needed, for each methodological component. For more information on the top two 'Developments needed', please see section 'Providing users with efficient access to the information'.

outcomes (full century time horizon, emission types necessary for the assessment reported)[31].

Some specific tools may facilitate the quality control and updating process, such as the Python packages Silicone and pyam. These packages help to complete the missing emissions species[30] and to analyse and visualize scenario databases, respectively[32]. The recent development of feasibility metrics[33,34] may also offer new perspectives for exclusion criteria.

After individual scenarios have been removed, the ensemble has to be considered in its entirety, to identify potential biases (block 3 in Fig. 3). As mitigation scenarios cannot be compared with an objective truth, biases are here defined as deviations from the distribution of assumptions or models desired by the analysts for the study. For instance, to analyse how mitigation costs increase with lower temperature targets, the analysts may want to have a similar number of scenarios per temperature outcome. However, it has been observed in ensembles that only the most optimistic models reported pathways reaching the most stringent targets, which introduced biases in terms of which models are represented for the different temperature levels[35]. Therefore, biases in our terminology in this paper correspond to any assumptions, scenarios or models being over- or under-represented in the ensemble, compared with the desired distribution for the intended use. This includes assumptions considered too optimistic on maturity of new technologies (for example, bioenergy with carbon capture and storage) or too pessimistic on other new technologies' costs (for example, renewables)[36], or ranges of economic growth assumptions that may be considered too low[37] or too high[38]. Some types of scenario may be over-represented, with imbalances compared with what is desired, between 1.5 °C or 2 °C scenarios and medium-level emission scenarios[39]; or between the exploration of energy supply-side and demand-side mitigation options[40]. Finally, some models or model types may be over- or under-represented in the ensemble, such that structural uncertainty in model representations is not covered to the extent desired even in a large scenario ensemble[41].

As there is limited practice in bias correction of climate change mitigation scenario ensembles (a notable exception is ref. [35]), developing and applying methods to correct and deal with ensemble biases are crucial next steps. First, reporting the biases identified alongside the analysis results is good practice. Second, statistical techniques can help to compensate for missing data (models, scenarios or assumptions), for example, through meta-modelling[42] or regression[35]. The latter reference has applied regression techniques to overcome the bias induced by the fact that only 'optimistic' models (that is, those models finding lower mitigation costs) reach the lowest mitigation targets. Third, potential avenues include developing weighting schemes for models or scenarios, following some practices implemented with climate scenarios[43,44]. Such weighting schemes can be based on inter-model distance of outputs, inputs or model characteristics, as experienced through hierarchical clustering in climate science[45], and could be based on recently developed models' diagnostics[46].

Selecting scenarios from the ensemble

The use of a scenario ensemble for analysis or decision support may require prioritizing a smaller number of scenarios aligned with the specific purpose. Selecting a subset of scenarios can help to focus on the most relevant pathways, communicate to non-experts by simplifying the scenario space[47] or increase the tractability of information for further analysis. The dominant practice in scenario ensemble uses and assessment reviews, such as those of the IPCC, relies on qualitative selection processes based on deliberation and consultation. It has been applied, for example, to the selection of illustrative pathways by IPCC authors[48,49]. The application of quantitative techniques can take the process a step further—particularly in terms of transparency and robustness—by making the selection criteria and process explicit. Here we focus on those techniques that may be guided by desirability, plausibility or diversity criteria (Fig. 4).

A subset of scenarios may be selected based on specific desirable or undesirable outcomes (block 1 in Fig. 4), such as emissions targets. Techniques to do this have recently been developed and applied in the context of model-based decision-making under uncertainty[21]. For instance, a scenario discovery approach[50] can highlight assumptions that lead scenarios to specified decision-relevant outcomes or vulnerabilities, such as the exceedance of a given threshold of temperature change[23]. Other examples of this approach include refs. [24–26] and are given in the Supplementary Information (illustrative case 7). This approach uses statistical techniques such as the patient rule induction method (PRIM)[51] or classification and regression trees (CART)[52] to identify the combinations of drivers or assumptions shared by decision-relevant scenarios. Key developments include linking this approach with qualitative methods to test the

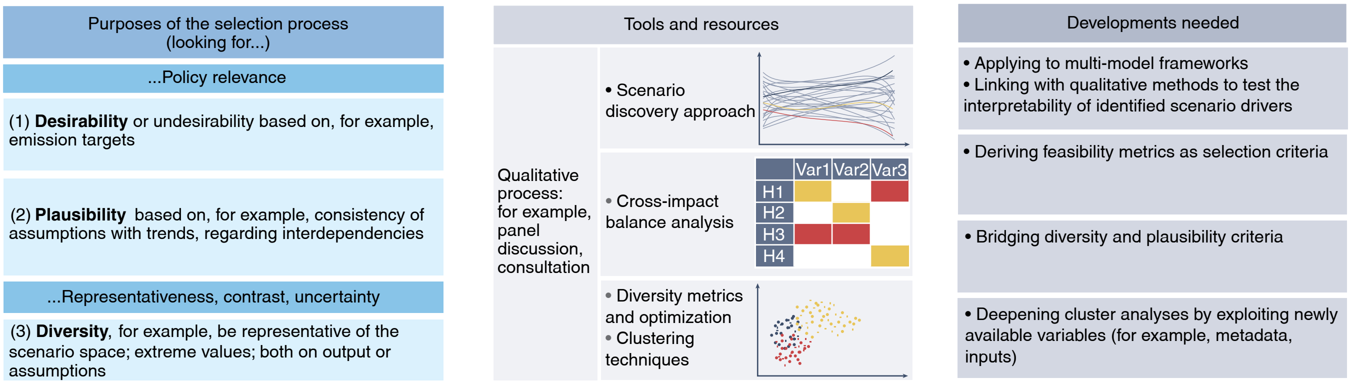

Fig. 4 | Methodological components to single out scenarios. The figure summarizes the existing tools and resources, as well as developments needed, depending on the purpose of the selection.

interpretability of identified scenario drivers and applying these techniques to multi-model scenario frameworks.

The analysts may also apply plausibility criteria to select a subset of scenarios (block 2 in Fig. 4). The perspective of plausibility has been applied in several studies, focusing on internal consistency of the scenarios. Self-consistent scenarios depict combinations of scenario assumptions that are coherent with current knowledge regarding their trends and interdependencies[53,54]. Consistency can be systematically assessed using structured methods such as cross-impact balance analysis[55]. This technique decomposes scenario assumptions into discrete elements, then elicits expert judgements about the expected direction of influence between each pair of elements. A retrospective application of this technique to the IPCC's *Special Report on Emissions Scenarios* (SRES) scenarios led to questioning the choice of the four storylines highlighted in the report[56]. The analysis revealed a wide variation in the internal consistency of the storylines, while identifying some highly consistent and policy-relevant scenarios under-represented in the SRES scenarios set[56]. Beyond the consistency perspective, recent developments that assess scenarios along feasibility dimensions offer new perspectives to guide the choice of the most plausible scenarios[33,34].

The selection can also seek to represent the diversity of the ensemble (block 3 in Fig. 4). It aims to extract relevant and tractable information for further analysis, or can contribute to avoid information overload and 'scenario fatigue' in participatory settings[57]. The intentions may be (1) to ensure maximum coverage of the original ensemble space[10]; (2) to capture uncertainty; and (3) to capture contrasting pairs or groups (for example, delayed versus early peak of global emissions or mitigation pathways with versus without carbon capture and storage). Formal diversity metrics can guide the selection[53], by identifying scenarios that lead to extreme values on outcome indicators[58] or that are maximally different in their assumptions[59]. Using such metrics, computationally efficient 'distance-to-selected' techniques[59] provide a way to identify under-represented scenarios in existing sets, as applied with Swiss electricity supply scenarios[60]. Parallel research has applied clustering techniques to identify diverse groups of scenarios, which present different behaviours over time[61] or different patterns across multiple outcome indicators[62,63]. A representative scenario can then be picked from each cluster. This systematic selection of diverse scenarios offers an alternative to a scenario set designed through a story-and-simulation method[64], potentially broadening the coverage of future possibilities beyond chosen narratives. Extensive exploration of scenarios via clustering still deserves further research, as an unprecedented number of scenario inputs, outputs, indicators and metadata on which to cluster becomes available. Measures of scenario diversity and plausibility can, in principle, complement each other[59], although the possible trade-offs between these perspectives for the selection of scenarios have yet to be systematically evaluated[53].

By helping analysts avoid ad hoc choices, these systematic selection techniques can support reproducible workflows and improve the transparency and credibility of the analyses. Nonetheless, certain challenges remain. First, diversity-related techniques bear the risk of highlighting outliers in the ensemble. The expert assessment of scenario consistency, in turn, will be influenced by the subjective views of the respondents[65] and will not reflect unexpected future changes in the structural relationships between scenario drivers[66]. Finally, when communicating a small number of scenarios, analysts should ensure that the selected scenarios are not framed in a way that attenuates uncertainty and gives overconfidence[67].

Exploring the full scenario ensemble

As an alternative approach to scenario selection, the exploration of a full ensemble can also bring new insights. By embracing a full set of scenarios, analyses can reflect the entirety of the space that scenarios have explored. Analysis can highlight results that are robust to the uncertainties covered or, on the contrary, illuminate the key factors influencing results. Such insights on the uncertainties that matter most can guide further research or inform decision-making under uncertainty.

The most common practice using entire scenario ensembles is simply to calculate descriptive statistics of the ensemble, such as in IPCC reports where outputs of the ensembles are synthesized by their median values and ranges in tables and figures[48,49]. While such syntheses carry important information about available options, they cannot be interpreted as a statistical sample or in terms of agreement or likelihood of a specific outcome. This applies especially to unstructured ensembles that have been collected from various sources. The ranges, and medians, of results reflect only the options that have been explored in the studies that produced the scenarios. Finally, when the distribution of results in a scenario ensemble is used as such, it is important to acknowledge that there is the implicit assumption that all scenarios in the ensemble are equiprobable. Therefore, biases of the ensemble, if not corrected in a preliminary step (section Pre-processing the scenario ensemble), are propagated to the use case.

Beyond describing the distribution of results, some methods, based on global sensitivity analysis[68], can disentangle the uncertain factors that influence this distribution the most. Such methods have been applied to single-model structured ensembles to highlight, for instance, the main uncertain drivers of energy security indicators[69], of investment needs for transport infrastructure[70], and of emissions and mitigation costs[25]. A further step to understand the robustness of those insights is to combine those methods with qualitative assessments of underlying assumptions[71]. A few studies have applied methods from global sensitivity analysis to multi-model structured ensembles[72,73], but such methods are not suited to unstructured ensembles and may be limited by the (un)availability of scenario metadata. Results of regression-based or variance-based analyses should be treated with care, because they could be an artefact of the set of scenarios in the ensemble and may differ from real-world relationships.

In the context of multi-model ensembles, and unstructured ensembles, meta-modelling techniques using multiple regression analysis can be used to quantify the relative importance of uncertain factors and different model structures. Applications have investigated uncertainties in land-cover projections[74], in the costs of achieving climate targets[75], in carbon price dynamics in ambitious mitigation scenarios[76], and in carbon dioxide removal deployment[77]. More complex forms of such meta-modelling techniques have been used in scenario ensembles beyond the field of climate mitigation, such as considering nonlinearities in the scenario drivers[78]. Analysts wishing to apply these sophisticated techniques in the context of climate mitigation scenarios might be constrained by the limited number of scenarios (typically often only a few hundred), and the potentially large number of drivers. Here, recent methodological advances in Bayesian analysis can be used effectively to adaptively shrink the number of drivers[79].

One avenue to go beyond implicit equiprobability of scenarios, and that can be an alternative route to the bias correction methods discussed above, is to assign probabilities to scenarios. This avenue has raised strong debates on the relevance of assigning (subjective) probabilities to emission scenarios[67,80,81], and different judgements on the likelihood of scenarios[82]. Past performance of scenarios could be used to quantify future uncertainties, as demonstrated in a case study on US energy scenarios[83].

To avoid reliance on potentially problematic probabilities, non-probabilistic methods to use scenario ensembles have started to be applied[26,84]. For instance, ensembles of mitigation scenarios could be used to identify mitigation strategies that perform well in the majority of cases, or that avoid the worst outcomes. Recognizing that decisions related to climate change mitigation have to be taken in a context of deep uncertainty, where reliable predictions or probabilities cannot be provided, decision-support tools inspired from decision-making under uncertainty approaches[21] should be further developed and applied to mitigation scenario ensembles. Such methods would allow one to test how alternative decisions would perform across a wide range of plausible futures, and help decision-makers identify robust strategies.

Providing users with efficient access to the information

Provision of mitigation scenarios needs to bridge a usability gap to facilitate their effective application in real-world decision-making in the realms of policy, business and civil society[7,85,86]. Reference [87] explained this usability gap by (1) the perceived fit or saliency of new information for the users[27], (2) the interplay between new information and the users' existing practices and (3) the quality of interaction between information users, analysts and scenario producers. This final step gives special attention to the interface with the users of the information produced, and especially to (1) communication and visualization tools, and (2) documentation of scenarios and ensembles, with emphasis on metadata.

First, ensuring the relevance of mitigation scenario ensembles for new types of end-user entails new requirements for decision-support and communication tools. These tools include interactive visual analytic frameworks that can help tailor the scenario information to end-users[88,89]. In the context of integrated assessment modelling scenarios, a recent example is the Integrated Assessment Modeling Consortium (IAMC) 1.5 °C Scenario Explorer hosted by the International Institute for Applied Systems Analysis (IIASA)[6,90] that enables interactive access to 414 scenarios compiled for the IPCC SR1.5 report. The interactive visualization of scenario ensembles can also focus on specific dimensions that are critical for applied policymaking, such as investment requirements for fulfilling the Paris Agreement[91] or energy, emission and economic indicators for the global stocktake in the Paris Agreement[4]. Empirical evaluations of interactive tools and visuals with users can help to improve functionality and design[85,92,93]. The choice of visualization tools can directly impact the end-users' perceptions of the scientific message[94,95], and the most adequate tool to foster understanding and appropriation strongly depends on the users' previous knowledge and skills[93].

The combination of analytical techniques with interactive visualization tools has so far been underused in research on mitigation scenarios. The algorithms for scenario discovery, clustering and diversity analysis are computationally efficient and available in open-source versions[96–98]. Integrating these tools for analysis and decision support with existing visualization platforms[6] would facilitate and foster their uses.

Second, increasing credibility and legitimacy involves meeting the expectations of fellow researchers, policymakers and the wider public that scientific meta-analysis of quantitative scenarios is transparent and reproducible. The assessment in IPCC SR1.5 raised the bar in that regard by making publicly available the notebooks that generated many headline statements, figures and descriptive statistics in the report. These notebooks are based on an open-source Python package pyam[32], initiated to support the SR1.5 assessment and further developed by the modelling community. Such a practice encourages transparent use of scenario ensembles, ensuring compliance with the FAIR (findable, accessible, interoperable, reusable) guiding principles for data management[99]. Further improvements are still needed, in particular in documenting how the scenario ensembles were designed, the details of the modelling protocols and the specificities of the models used. More extensive provision of such metadata would enable usability for a wider range of users, and is a prerequisite for further applications of the methods discussed in this Perspective. We call upon the IAMC, or a similar organization, to coordinate the compilation activities for scenario ensembles, and associated metadata, into a common place. It would benefit from building on the templates developed for IPCC databases and the practice of harmonized models' documentation (https://www.iamc-documentation.eu/) and diagnostics[46].

Taking stock and ways forward

More extensive use of scenario ensembles has the potential to bring new and more robust insights to meet diverse end-users' needs, but also raises challenges to fully exploit this potential. By reviewing scenario ensembles' uses, limitations and methodological issues, as well as available approaches to address those and critical points of development needed, we highlighted three key steps relevant to their appropriate use. Finally, we suggest seven points to foster good practices to enable methodologically sound use of scenario ensembles and effectively provide benefits to users and policy-relevant insight.

For scenario producers and modelling communities:

(1) Make scenario data (both input and output), and metadata, accessible along FAIR principles.
(2) Develop community tools, templates and practices to share scenario data and metadata in harmonized ways.

For scenario ensemble analysts:

(3) Engage with the final users of the information to understand their needs and define the purpose and ambition of the intended use.

(4) Ensure the adequacy of the specificities of the ensemble used with the study objective.
(5) Select the processing and analysis techniques suitable for the ensemble; check fitness for the purpose of the intended use by considering salience, credibility and legitimacy issues.
(6) Ensure transparency, usability and interpretability of the information produced, drawing on FAIR principles and documenting the choices and tools used for the analysis.
For final users of information from scenario ensembles:
(7) Get information about the scenario ensembles and analysis techniques, and their limitations, when interpreting and using the information produced.

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Author contributions

C.G. led the work. C.G. and T.L.G. jointly prepared the manuscript and T.L.G. designed the figures. All authors contributed to the text.

Competing interests

The authors declare no competing interests.

Additional information

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