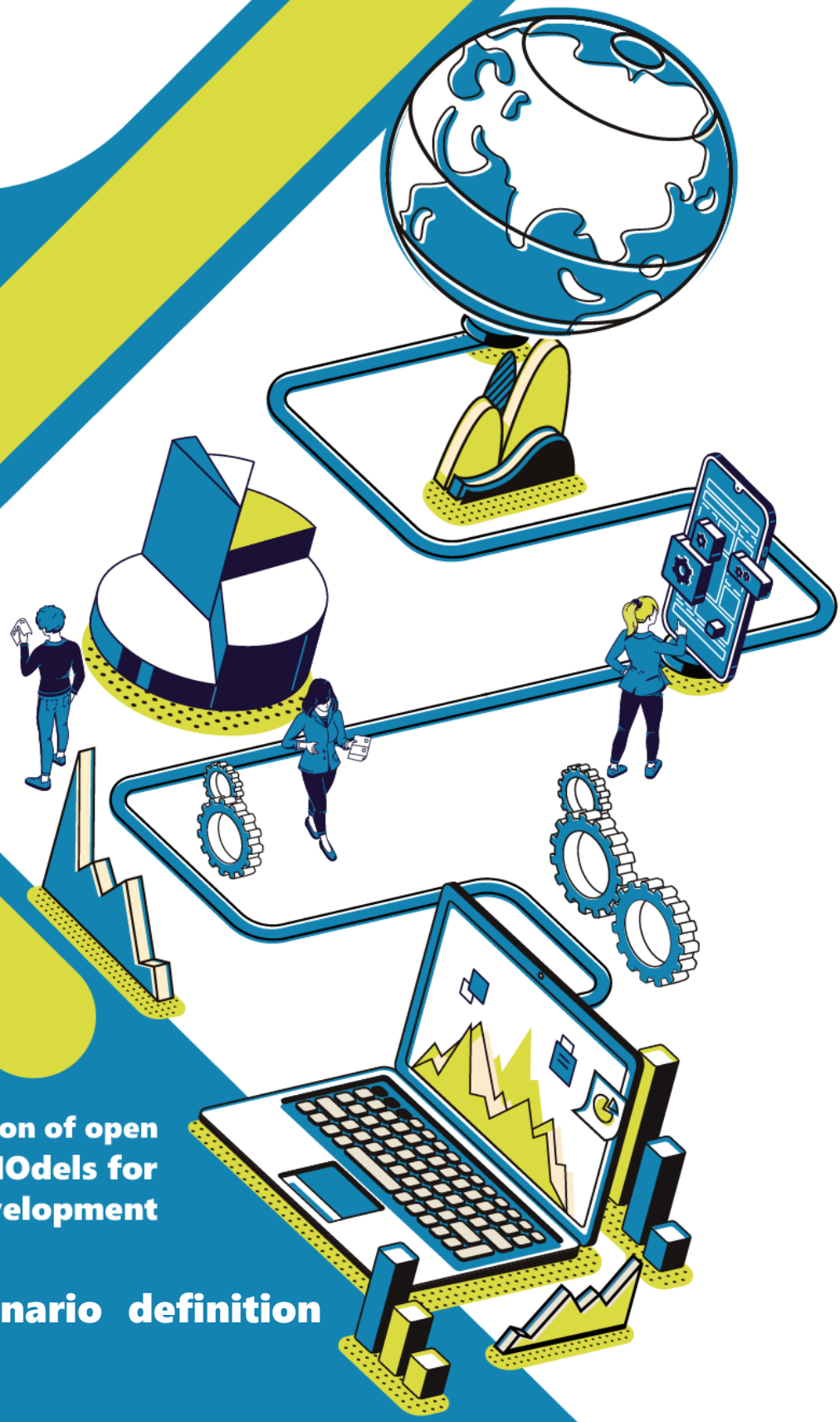
DIAMOND

www.climate-diamond.eu



Delivering the next generation of open Integrated Assessment MOdels for Net-zero, sustainable Development

D5.2 – A novel scenario definition space – Update

WP5 – Apply and Explore

30/05/2026

Funded by
the European Union

Disclaimer

The sole responsibility for the content of this publication lies with the authors. It does not necessarily reflect the opinion of the European Union. Neither CINEA nor the European Commission is responsible for any use that may be made of the information contained therein.

Copyright Message

This report, if not confidential, is licensed under a Creative Commons Attribution 4.0 International License (CC BY 4.0); a copy is available here: https://creativecommons.org/licenses/by/4.0/. You are free to share (copy and redistribute the material in any medium or format) and adapt (remix, transform, and build upon the material for any purpose, even commercially) under the following terms: (i) attribution (you must give appropriate credit, provide a link to the license, and indicate if changes were made; you may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use); (ii) no additional restrictions (you may not apply legal terms or technological measures that legally restrict others from doing anything the license permits).

Grant Agreement Number	101081179		Acronym	DIAMOND
Full Title	Delivering the next generation of open Integrated Assessment MOdels for Net-zero, sustainable Development			
Topic	HORIZON-CL5-2022-D1-02			
Funding scheme	HORIZON EUROPE, RIA – Research and Innovation Action			
Start Date	December 2022	**Duration**	48 Months	
Project URL	http://www.climate-diamond.eu/			
EU Project Advisor	Silvia Vaghi			
Project Coordinator	Institute of Communications and Computer Systems - ICCS			
Deliverable	D5.2 – A novel scenario definition space (Update)			
Work Package	WP5 – Apply and Explore			
Date of Delivery	**Contractual**	31/05/2026	**Actual**	30/05/2026
Nature	Report	**Dissemination**	Public	
Lead Beneficiary	CICERO Senter for Klimaforskning			
Responsible Author	Glen Peters	**Email**	glen.peters@cicero.oslo.no	
	CICERO	**Phone**	+4792891638	
Contributors	Glen P Peters, Jan Ivar Korsbakken, Shivika Mittal, Ben Sanderson (CICERO), Konstantinos Koasidis, Alexandros Nikas (ICCS); Steve Pye (UCL); Mark Sanders (UM); Marten van der Kam (UNIBAS); Alaa Al Khourdajie (Imperial); Theo Rouhette (BC3)			
Reviewer(s)	Natasha Frilingou, Konstantinos Koasidis, Alexandros Nikas (ICCS)			
Keywords	Scenarios, Scenario Space, Storylines, NDC 3.0, Climate Assessment			

EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

The report offers guidance to consortium members and other entities outside the consortium to help them conduct climate assessments of different emissions trajectories from energy and industrial processes. The second and fifth section in the report is also relevant for consortium members and external stakeholders to understand the definition of the model-scenario space, how stakeholder insights are incorporated into the scenario design process, and consequently how the scenario space is extended. Results presented on the baseline scenario may also inform policymakers on temperature and energy implications of the updated NDCs.

3. Short summary of results (<250 words)

This deliverable addresses the challenge of characterising the full hypothetical scenario space used in climate research, which is only partially explored and therefore difficult to map for gaps and uncertainties. The climate assessment pipeline takes existing scenarios and enhances them through post-processing to enable consistent climate evaluation. This includes selecting relevant scenarios, harmonising emissions data, and infilling missing climate-relevant species such as sulphur emissions. These processed scenarios are then analysed using simple climate models to estimate temperature outcomes. Each step introduces additional, often poorly constrained uncertainties. The report also highlights that IPCC-assessed scenarios represent only a biased subset of the wider literature due to curation choices, limiting the coverage of the full scenario space. To address this, we develop a conceptual framing of the broader scenario space—building on the initial conception presented in D5.1—and identify ways to better detect and fill gaps.

After characterising this scenario space and the uncertainty pipeline, the report presents the baseline scenario of DIAMOND based on the updated NDCs and NECPs and then outlines the scenario space co-defined through stakeholder engagement. The report focuses on the scenario protocols that produce thematic storyline-based scenarios (e.g., enhanced circularity efforts, or implications of disruptions) reflecting stakeholder priorities, while at the same time better spanning key uncertainties in emissions pathways, harmonisation choices, land-use assumptions, and climate response, improving the robustness of climate uncertainty assessment.

4. Evidence of accomplishment

This report and the paper based on Section 2, which is currently under review in the *Climate Policy* journal.

Funded by
the European Union

Preface

DIAMOND will update, upgrade, and fully open six Integrated Assessment Models (IAMs) that are emblematic in scientific and policy processes, improving their sectoral and technological detail, spatiotemporal resolution, and geographic granularity. It will further enhance modelling capacity to assess the feasibility and desirability of Paris-compliant mitigation pathways, their interplay with adaptation, circular economy, and other SDGs, their distributional and equity effects, and their resilience to extremes, as well as robust risk management and investment strategies. This will be done via integration of tools and insights from psychology, finance research, behavioural and labour economics, operational research, and physical science. The project will develop a transdisciplinary scientific approach to legitimise the implementation process and co-create research questions that stretch the frontiers of climate science, as well as establish vibrant communities of practice to transparently open model enhancements and to develop capacities, thereby lowering the entrance barriers to the established IAM community.

ICCS	INSTITUTE OF COMMUNICATIONS AND COMPUTER SYSTEMS	EL
BC3	ASOCIACION BC3 BASQUE CENTRE FOR CLIMATE CHANGE - KLIMA ALDAKETA IKERGAI	ES
CESAR	KRATENA KURT	AT
CICERO	CICERO SENTER FOR KLIMAFORSKNING	NO
CYI	THE CYPRUS INSTITUTE	CY
E4SMA	ENERGY ENGINEERING ECONOMIC ENVIRONMENT SYSTEMS MODELING AND ANALYSIS SRL	IT
HOLISTIC	HOLISTIC IKE	EL
COMILLAS	UNIVERSIDAD PONTIFICIA COMILLAS	ES
ISINNOVA	ISTITUTO DI STUDI PER L'INTEGRAZIONE DEI SISTEMI (I.S.I.S) - SOCIETA'COOPERATIVA	IT
SEURECO	SEURECO SOCIETE EUROPEENNE D'ECONOMIE SARL	FR
UM	UNIVERSITEIT MAASTRICHT	NL
ESMIA	ESMIA CONSULTANTS INC.	CA
USMF	THE UNIVERSITY OF MARYLAND FOUNDATIION INC	US
UMD	UNIVERSITY OF MARYLAND	US
EPFL	ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE	CH
ETH	EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH	CH
UNIBAS	UNIVERSITAT BASEL	CH
Imperial	IMPERIAL COLLEGE OF SCIENCE TECHNOLOGY AND MEDICINE	UK
Oxford	THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITY OF OXFORD	UK
UCL	UNIVERSITY COLLEGE LONDON	UK

Executive Summary

Despite the existence of a vast number of scenarios produced by the energy-climate-economy modelling community, the full hypothetical scenario space spanning all potential and available scenarios is difficult to characterise. Consequently, identifying gaps in this scenario space and fully exploring uncertainties remain a key challenge. This report aims to better **characterise the scenario space** and identify key uncertainties in the assessment pipeline. The uncertainties considered cover both the scenario space and the scenario climate assessment pipeline. As part of this task, Deliverable D5.1 (submitted in January 2024) had focused on a rigorous review of the scenario pipeline uncertainties and the scenario definition space. This deliverable in turn performs a deeper analysis on the scenario pipeline uncertainties and identify how the prescribed DIAMOND scenarios broaden the scenario definition space.

In particular, here we first discuss persisting gaps in the scenario development field, arguing that the hypothetical scenario space is only partially filled. The scenarios assessed in the IPCC process are only a subset of scenarios in the literature, and may form a biased sample based on the scenarios' curation process used. This is likely unavoidable. We provide a more thorough conceptual background to the scenario space—building on the initial conception developed in D5.1—and identify ways that its characterisation may be improved within DIAMOND.

Towards populating the scenario space, the **climate assessment pipeline** is a critical step, aiming to take existing scenarios and supplement them with additional data to provide a more comprehensive assessment. Within the climate context, scenarios are often constrained by cumulative CO_2 emissions or radiative forcing as a proxy for climate. On top of such established processes, a more comprehensive climate assessment is added through post-processing steps. Notably, several steps are often required that modify the original scenario to facilitate a consistent climate assessment. Depending on the research question, scenarios may go through a variety of post-processing steps to help select the relevant scenarios for the research question (e.g., vetting against relevant criteria). The climate assessment might need to modify the scenario output emissions to match the emissions data used in the climate assessment (harmonisation) and may need to supplement the scenario output with additional climate relevant species (e.g., infill the scenarios with sulfur emissions if they are not provided by the model). After these steps, a simple climate model is used to estimate temperature and uncertainties. All these steps in providing a climate assessment create additional uncertainties, which are poorly constrained. Building on top of the key uncertainties outlined in the previous iteration of the deliverable, here we expand this pipeline through alternative climate assessment methods and updates on simple climate modelling.

We then proceed to outline the design of activities to be performed within DIAMOND in order to populate and expand this scenario space. A first step in this process was the establishment of a **common baseline scenario** implemented across all six IAMs of the project, reflecting the current ambition that was outlined in the updated Nationally Determined Contributions (NDCs) globally and the latest batch of the National Energy and Climate Plans (NECPs) in the EU. Based on the preliminary implementation of this protocol in the IAMs—acknowledging that some models are still under development—we provide energy implications, as well as a temperature assessment employing the pipeline described above. We then provide **a set of protocols that produce thematic storyline-based scenarios** (e.g., enhanced circularity efforts, or implications of disruptions) reflecting stakeholder priorities elicited as part of WP2 activities, while at the same time better spanning key uncertainties in emissions pathways, harmonisation choices, land-use assumptions, and climate response, improving the robustness of climate uncertainty assessment. These protocols will feed into the remaining tasks under WP5, which will aim to develop the scenarios through the models and modules developed in the project. Later in the DIAMOND project (Task 5.7), we will assess how the scenarios co-created in the DIAMOND project may modify and fill gaps in the scenario space.

Funded by
the European Union

Contents

1 Introduction 1
1.1 Scope 1
2 Reimagining the model-scenario space 2
2.1 Introduction 2
2.2 Defining what constitutes a scenario 3
2.3 The model-scenario space 4
2.3.1 Existing scenarios used in the climate context 5
2.3.2 SSPs and the model-scenario space 9
2.3.3 Scenario databases 10
2.3.4 Other scenarios 10
2.3.5 The hypothetical model-scenario space 12
2.3.6 Characterising the model-scenario space 14
2.3.7 Literature review 14
2.3.8 Emerging quantitative methods 15
2.3.9 Scenario co-design 16
2.3.10 Conclusions 16
3 Climate assessment and a climate assessment pipeline 18
3.1 Introduction: Summary of climate assessment trade-offs 18
3.2 Role of infilling, and harmonisation and vetting as enablers 19
3.2.1 Harmonisation as a requirement for safe infilling 19
3.2.2 Vetting as a requirement for safe harmonisation 19
3.2.3 Limited impact of harmonisation and infilling given vetting criteria 20
3.3 Alternative climate assessment methods for DIAMOND 20
3.3.1 The case for alternatives to the climate assessment pipeline 20
3.3.2 Cumulative-emissions constraints: The "temperature sandwich" method 21
3.3.3 Direct infilling: Skipping the climate-modelling step 25
3.3.4 Time-series regression: PCA on time-dependent, correlated emissions 26
3.3.5 Outer-bounds infilling: Maximum ranges given modelled emissions and years 27
3.4 Updates on simple climate modelling in DIAMOND 28
4 Development of a common baseline scenario 30
4.1 Rationale and overarching approach 30
4.2 Protocol for the common baseline scenario 32
4.3 Emissions and energy-system implications of updated commitments 35
4.3.1 Emissions 36
4.3.2 Temperature 39
4.3.3 Electricity Generation Mix 39
4.3.4 Primary Energy mix 40
4.3.5 Reflections on the current implementation of the baseline scenario 41
5 DIAMOND Scenario Narratives 42

Funded by the European Union

5.1 Task 5.2: Climate impacts and adaptation 42
5.1.1 RQ1: The impact of fire carbon emissions on land use pathways in the EU 42
5.2 Task 5.3: A bumpy road to net-zero: systematic assessment of disruptive events 45
5.3 Task 5.4: Stretching the frontiers – user-driven scenarios building on expanded modelling framework 47
5.3.1 The role of circular economy policies in decarbonising steel, cement and aluminium sectors 47
5.3.2 Policy Scenarios for Finance in IAMs 50
5.3.3 Policy Experiments for Labour Market Extensions 52
5.3.4 Policy Experiments for Final Demand 54
5.3.5 People in Transition 55
5.4 Task 5.5: Expanding the SDG target space: placing climate action in broader sustainable development 57
5.4.1 Overarching objectives 57
5.4.2 Stakeholder insights 57
5.4.3 Design of Activities 58
6 Concluding Remark 60
References 61

Table of Figures

Figure 1. SSP population projections 7
Figure 2. Primary energy in different SSP (boxes)-RCP (line colours) combinations 11
Figure 3. Hypothetical scenarios space of possible (dark blue), existing (green), and assessed by the IPCC (light blue) scenarios 12
Figure 4. Temperature trajectories and ranges estimated using the "temperature sandwich" approach 24
Figure 5. CO_2 emission trajectories for the DIAMOND baseline scenarios 25
Figure 6. Comparison between the 2nd and 3rd round of NDC submissions. 31
Figure 7. NECP emission target for European member states without LULUCF 32
Figure 8. NECP emission target for European member states with LULUCF 32
Figure 9. Emissions Pathways from different models 38
Figure 10. Change in the energy related emissions in European member states 38
Figure 11. Electricity generation mix in 2019, 2035, and 2050 40
Figure 12. Primary Energy mix in 2019, 2035, and 2050 41
Figure 13. Modelling framework for the study of fire impacts on land system mitigation using the modelling framework IAM-FIRE and the integrated assessment models GCAM-Europe and CLEWs. 44
Figure 14. Conceptual linkage and information flow between ENGAGE and OMNIA 50

Table of Tables

Table 1. Illustration of different scenario types in the hypothetical model scenario space 13
Table 2. Model ensemble 35
Table 3. Temperature in 2050 and 2100 39
Table 4. Scenario design to assess the role of fire impacts on the European Union climate policy package Fit-for-55 44
Table 5. Proposed CE policies for consideration in scenarios 48
Table 6. Regional implementation of CE policy packages 48
Table 7. Research questions received and addressed for policy scenarios of People in Transition 55

1 Introduction

The EU Horizon Europe project "Delivering the next generation of open Integrated Assessment MOdels for Net-zero, sustainable Development" (DIAMOND) has been updating, upgrading, and delivering six fully open Integrated Assessment Models (IAMs) that are emblematic in scientific and policy processes, improving their sectoral and technological detail, spatiotemporal resolution, and geographic granularity. These IAMs will then be applied to user-driven research questions to explore the new modelling capabilities of the models. Conceptually, the DIAMOND project aims to expand and enhance the 'scenario definition space' in two key dimensions: user relevance and model capabilities.

This deliverable represents work undertaken after the submission of the first deliverable D5.1 as part of Task 5.1. In the updated deliverable, we define the hypothetical model-scenario space and discuss how and why much of this space remains unexplored. We argue that the literature spans a subsection of this hypothetical space, and that the models and scenarios assessed by the IPCC span an even smaller subspace. The properties of the IPCC-assessed model-scenario space remain largely uncharacterised. An uneven, biased sampling of the model-scenario space may limit, and potentially skew, key findings in mitigation assessments. We demonstrate that the scenario literature is not a random sample of the model-scenario population, by drawing on a) the literature, b) quantitative and qualitative methods, and c) transdisciplinary science principles. As comprehensive sampling of the model-scenario space could potentially be infeasible, we argue for a shift in assessment methodology. We propose a more robust, question-driven approach, designed to bring multiple lines of evidence: stratifying scenario selection across diverse sources to answer clear, pre-defined research questions; utilising greater model and scenario diversity to widen coverage of structural and parametric uncertainties; and greater utilisation of non-modelled scenarios to complement quantitative analysis.

In Section 2 we describe the conceptual model-scenario definition space, and then in Section 3 we provide an update on the climate assessment pipelines, as well as new methods for climate assessment of scenarios and simple climate models. In Section 4, we provide details about the baseline scenario protocol and preliminary results in terms of energy and emissions implications of revised national commitments. In the last section, we describe the protocols for the DIAMOND scenarios narratives to be implemented in WP5 to answer to pertinent stakeholder priorities arising from the codesign process.

1.1 Scope

The outcome of this task is broken down into two deliverables. The first (D5.1) was submitted in January 2024 and focused on a systematic review of scenario pipeline uncertainties and the scenario definition space. This deliverable (D5.2) revises the scenario definition space and identifies how the DIAMOND scenarios broaden it, as well as the energy and climate implications of the new round of NDC 3.0 submissions made by nations to the UNFCCC.

Funded by
the European Union

2 Reimagining the model-scenario space

2.1 Introduction

Scenarios are among the key tools for understanding climate change, its consequences, and potential solutions. Scenarios have also been a core part of Intergovernmental Panel on Climate Change (IPCC) processes since with the First Assessment Report (Bernthal et al., 1990). Because of their prominence (van Beek, Hajer, Pelzer, van Vuuren, & Cassen, 2020), including in the media, it is perhaps unsurprising that their role in the IPCC has been critiqued over the years (Pedersen et al., 2022). Critiques either focus on the scenarios or the models used to quantify them. Here, we focus on the completeness of the space of model-scenario combinations, on what is missing from the space, and on how the purpose of scenarios and the societal actors involved in the processes limit the model-scenario space (Lahn, Sognnaes, & Hermansen, 2025; Peters, Al Khourdajie, Sognnaes, & Sanderson, 2023). Early IPCC Assessment Reports focussed on covering a wide range of emission outcomes, like low- and high-emission scenarios (Pedersen et al., 2022), and whether there were missing scenarios is potentially only a question of whether higher or lower scenarios existed but were not assessed. In contrast, more recent IPCC Assessment Reports have focused on mitigation scenarios (IPCC, 2014, 2022b; Rogelj et al., 2018), so the meaning of missing or overlooked scenarios differs.

The state-of-the-art in defining the 'model-scenario space' is through voluntary submissions to scenario databases (Huppmann, Rogelj, Krey, Kriegler, & Riahi, 2018) . These represent a range of research questions developed by individual modelling groups—often without stakeholder engagement (A. Nikas et al., 2021) or guiding research questions to address nuanced understandings or needs in relation to knowledge gaps(Stephanie Briers & Vienni-Baptista, 2024) . Moreover, owing to curation, scenario databases are not comprehensive but represent a mosaic of research questions (Peters et al., 2023), often leading to the term 'ensemble of opportunity' (Huppmann, Rogelj, Kriegler, Krey, et al., 2018; Peters et al., 2023). Based on these databases, IPCC authors provide statistical summaries of policy-relevant variables (Riahi et al., 2022b), such as emission reduction levels in 2030, net zero years, or fossil fuel shares in 2050. However, few scenarios have been constructed to provide a representative statistical sample for these specific policy questions. Therefore, the robustness of statistical summaries is entirely conditional on how representative the database properties are (Sognnaes & Peters, 2025). Given the lack of structure behind scenario curation, researchers themselves have decided what is important to policymakers (Silke Beck & Mahony, 2017; S. Beck & Oomen, 2021; Krawczyk & Braun, 2025) and thereby limited exploration of potentially more policy-relevant but underexplored areas of the model-scenario space (Koasidis, Nikas, & Doukas, 2023).

Here, we take aim at the space of available models and scenarios, how well they cover the broader mitigation literature and hypothetical model-scenario space, and the relevance of scenarios in the IPCC context of 'policy-relevant and yet policy-neutral, never policy-prescriptive (Hermansen, Boasson, & Peters, 2023) , with a view to characterising and expanding the model-scenario space. Building on earlier work showing the challenges of using scenario databases to answer policy-relevant questions (Dekker et al., 2023; Guivarch et al., 2022), we significantly expand on the debate by focusing on what is missing from the literature or databases. We do not aim to assess critiques of the models used to generate scenarios, though the 'model space' is also a worthy area for deeper investigation (Thompson, 2022). We then discuss the importance of clearly linking to research questions and subsets of models and scenarios relevant for those questions. We conclude with suggestions for advancing the policy relevance of the scenario literature feeding into future IPCC reports.

Funded by
the European Union

2.2 Defining what constitutes a scenario

Scenarios have long been used in different contexts, often relating to strategic planning or risk assessment (Bradfield, Wright, Burt, Cairns, & Van Der Heijden, 2005; Cordova-Pozo & Rouwette, 2023) . A scenario is often broadly defined as a series of potential events or futures, which can be used to assess, qualitatively or quantitatively, how these events or futures may be managed. Here, we focus specifically on the use of scenarios in IPCC assessment reports, which has a much more specific definition of scenarios.

The IPCC originally offered a rather generic definition of "emissions scenarios", while quantification using models (Houghton, Callander, & Varney, 1992):

"Projections of future emissions based on specific assumptions about key determinants, such as population, economic growth, technological change, land-use trends or emission control policies."

The IPCC "Climate Change 1994" report, which assessed the IS92 scenarios, outlined a method to assess scenarios (IPCC, 1994). Four purposes of scenarios were considered (reference scenarios, intervention scenarios, mitigation analysis, input to negotiations), which were then evaluated against a range of criteria, finding that the three most important criteria were comprehensiveness, detailed output, and diversity (a range of views). Three other criteria were mentioned as important (reproducibility, sensitivity analysis, internal consistency), while others were also assessed but found less important (documentation, disaggregation of data, reference scenarios, a range of policy actions, temporal calculations). The definition of scenario was clearly separated with methods to evaluate scenarios.

Since the IPCC Special Report on Emissions Scenarios (SRES), the definition of scenarios changed to its current form (IPCC, 2022a, 2022b).

"A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships."

The IPCC definition now encompasses concepts used to evaluate scenarios (e.g., plausible, coherent, internally consistent) originally used as criteria for assessing scenarios (IPCC, 1994). These terms are not defined, leaving it up to the scenario producer or user to define them. Coherent, internally consistent, and plausible could have different meanings depending on context, often contentious, and potentially dependent on the research question. For example, coherence and internal consistency have also been used in model soft-linking, ensuring consistency of scenario narrative. Plausibility is also a vague term, often linked to feasible or desirable (Jewell & Cherp, 2019) , and its assessment may be constrained by how researchers envision or conceive the future, potentially influenced by collective groupthink within the scientific community (McCollum, Gambhir, Rogelj, & Wilson, 2020). Turning these concepts from vague, implicit filters embedded into the definition into transparent, assessable notions that can be analysed and debated is critical (Skea, van Diemen, Portugal-Pereira, & Khourdajie, 2021). Allowing ambiguity to remain poses a significant challenge for robust assessments.

One could postulate if any existing scenarios meet the criteria in the current IPCC definition. For example, many scenarios have turned out poor at representing the dynamics of key technologies, such as nuclear (Keepin & Wynne, 1984), solar (Creutzig et al., 2017; Jaxa-Rozen & Trutnevyte, 2021) , or carbon capture and storage (CCS) (Kazlou, Cherp, & Jewell, 2024) . One could even argue a key application of scenarios is to explore futures, or sets of assumptions, that are not internally consistent, coherent, or plausible, as these are the ones difficult to manage and address (Gambhir et al., 2025) , such as disruptive (Al Khourdajie, et al., in preparation) or extreme scenarios (McCollum et al., 2020). Rather, the degree of a scenario's plausibility, coherence, or internal consistency should be a key finding of the assessment itself, not an element of its definition.

Funded by
the European Union

An overlooked aspect of a scenario is the scenario storyline, defined by the IPCC as a "narrative description of a scenario (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces and the dynamics of their evolution".

The scenario storyline is generally the driving element of a scenario. Storylines may be developed by individual researchers (or research groups) or in a deliberative process with a cross-section of interests. The goal is often to span different dimensions or uncertainties of a problem. The trade-offs and interactions between dimensions are sometimes reflected in a quadrant or 2x2 matrix approach (Amer, Daim, & Jetter, 2013). The field of 'futures thinking' primarily develops qualitative scenarios (Cork et al., 2023), without needing to link to models for quantification—i.e., a link to a model is not a prerequisite for a narrative to qualify as a scenario. Socio-technical scenarios follow the same logic, as either standalone narratives (Elzen, Geels, Hofman, & Green, 2004) or starting points to iteratively contribute to quantitative scenarios (Geels, McMeekin, & Pfluger, 2020). Qualitative scenarios are often used to brainstorm relevant challenges and uncertainties about the future(Böttcher et al., 2024), something of an added value in its own right.

The purpose of scenarios has changed considerably through IPCC assessment cycles. The IS92 scenarios had a specific research question around no policy intervention (Houghton et al., 1992) , partly in response to the strong political backlash on the original SA90 scenarios (van Beek et al., 2020). Later IPCC assessment cycles have only stated that scenarios should consider a wide range of outcomes (Pedersen et al., 2022). Notably, the IPCC identified no specific research questions or focus areas in SRES (IPCC, 2000) or later IPCC reports, providing instead section outlines for the assessment, within which authors have the latitude to formulate and address issues they deem pertinent to the section's mandate. Since the Fifth Assessment Report (AR5), scenario curation has been left up to the research community (Moss et al., 2010; Skea, Shukla, Al Khourdajie, & McCollum, 2021), with an increasing focus on mitigation as a key theme(K. Riahi et al., 2022; Rogelj et al., 2018). The growing focus on deep mitigation has, in turn, led to a scarcity of scenarios of moderate mitigation levels (van Ruijven, 2016). The criteria against which to assess scenarios, therefore, needs continuous revision, in line with changing purposes and new knowledge.

Given an ever-evolving purpose and knowledge, a more generic scenario definition that does not exclude valuable lines of evidence may be preferable(IPCC, 1994). We argue for a more generic definition, as originally used by the IPCC (Houghton et al., 1992), with terms such as internally consistent, coherent, or plausible evaluated as part of analysis or assessment. While the scenario literature would assumably specify a research question or purpose, when scenarios are submitted to a scenario database, the research question or purpose and constraints applied should be provided as metadata. An assessment of relevant factors could be harmonised across models and studies, and preferably undertaken by different research groups, to build multiple lines of evidence on key assessment criteria. This may require a new approach to scenario assessment, more in line with the approaches taken in the climate community (Peters et al., 2023).

2.3 The model-scenario space

In statistics, the concepts of a population (all possible members of a group) and a sample (a selection from the population) are at the centre of any empirical analysis. We propose the existence of a hypothetical "model-scenario space" covering all possible model-scenario combinations (i.e., the population). As in most statistical analyses, the first step is to assess whether a sample of the model-scenario space (e.g., a database) is statistically representative, in that it would return statistical outcomes reflecting the entire population. While seemingly abstract, this is a highly relevant point, as several Key Messages in the IPCC AR6 WGIII Summary for Policymakers (SPM) draw on statistical summaries of a scenario database, which have been shown to be non-representative (Sognnaes & Peters, 2025). While the issue has been noted, IPCC assessments have not addressed

the representativeness of IPCC scenario databases for specific purposes. This does not mean all quantitative analysis is invalid. Rather, it implies the type of analysis must change. Instead of reporting summary statistics that presume a representative sample (like medians or 5-95th percentiles), assessments should focus on methods characterising the properties of the non-random sample itself—such as identifying clusters, quantifying the influence of model structure, and analysing the drivers of specific outcomes—before using summary statistics.

In the physical climate sciences, one could expect that adding more (independent) observations improves the overall estimate, as the uncertainty space is inherently bounded by physical laws. The same is unlikely to hold for emission scenarios: these are driven by diverse, possibly conflicting economic-engineering theories or approaches, rather than unambiguous, universally accepted laws. Physics may be able to determine where a projectile will land, but not how civilisation will evolve. Moreover, emission scenario outcomes are not contingent predictions of physical variables but represent parts of potential mitigation strategies, which have no single "true" value. Multiple values are in this case not only possible, but expected, where each value is associated with different mitigation trade-offs.

The space of potential assumptions on socioeconomics, technologies, and policies, as well as their consequent outcomes, might be practically innumerable. The IIASA energy scenarios of the early 1980s were largely dominated by nuclear, with little consideration on then largely unknown technologies such as CCS and carbon dioxide removal (CDR). This does not mean they were wrong, but that they reflected the visions of the future conceived by the scenario producers at the time. The world changed, however, in ways not depicted or imagined in those scenarios. While the scenarios themselves may have remained insightful and provided useful information at the time, summary statistics of their future outcomes may have limited value (Huntington, Weyant, & Sweeney, 1982). Even if projections of coal, oil, or gas in those scenarios have turned out to be reasonable, it may be for the wrong reasons. This highlights a fundamental point: the goal of a scenario analysis should not be to find a statistical 'central tendency' or 'likely' future, but to map the consequences of assumptions. Therefore, the assessment's focus should shift from finding a median outcome toward understanding how different assumptions (e.g., about socioeconomics, technology, or policy) may change the outcome.

We break down our discussion into different types of scenarios, to identify how scenarios may miss parts of the model-scenario space. We first discuss scenarios that are regularly used in a climate context and reflect on the notion that a sample of the model-scenario space will unlikely be representative of the model-scenario population.

2.3.1 Existing scenarios used in the climate context

Here, we discuss existing scenarios used in the climate context, covering the narrative and quantification parts of a model-scenario combination. Most of the discussion is focussed on the Shared Socioeconomic Pathways (SSPs) due to their dominance in the climate literature, although we touch upon scenario databases and other scenarios used in a climate context more broadly.

2.3.1.1 Shared Socioeconomic Pathways (SSPs)

Alongside the Representative Concentration Pathways (RCPs), the SSPs have dominated climate literature since they were first envisaged (Moss et al., 2010). They were originally proposed to bypass the slow linear scenario generation process by facilitating the climate modelling and scenario communities to work in parallel, where the RCPs (levels of radiative forcing in 2100) were a common element across the two communities. Once the RCPs were decided, the climate modelling community (utilising RCPs) and the climate scenario community (producing scenarios consistent with the RCPs) worked in parallel. The work of the scenario community led to the SSPs.

SSPs development followed three broad steps (Keywan Riahi et al., 2017): 1) narratives, 2) quantified socioeconomic pathways and 3) baseline and mitigation scenarios.

After developing the SSP narratives (O'Neill et al., 2017), models were used to develop quantitative population and GDP projections (O'Neill et al., 2013), which were then used to estimate end-use demand, as input into IAMs to generate pathways for energy and emissions (Riahi et al., 2017) and land use (Popp et al., 2017). The initial pathways for the quantified SSPs were baseline scenarios, assuming zero climate policy (effectively, a carbon price of zero), with Shared Policy Assumptions (SPAs) later used to reach different levels of radiative forcing in 2100 (Kriegler et al., 2014). We now discuss each of these steps and the implications on the model-scenario space.

2.3.1.2 Narratives

The SSP narratives were developed as quadrants spanning the two axes, 'challenges to mitigation' and 'challenges to adaptation', while a 'middle-of-the-road' narrative (SSP2) was included in the centre (Brian C. O'Neill et al., 2017). The SSPs were largely built on the SRES scenarios and drew on expert meetings (Schweizer & O'Neill, 2013; Wilbanks & Ebi, 2014). The SSPs would likely look different if they involved different experts, including from developing countries, diverse user communities, and different academic communities. The SSPs share many elements of the earlier SRES scenarios and other scenario exercises (van Vuuren et al., 2013), indicating the importance of legacy in scenario development, potentially emphasised by the close networks of these communities (Cointe, 2024; Corbera, Calvet-Mir, Hughes, & Paterson, 2015).

The SSP narratives are not unique. The quadrants were decided to reflect challenges to climate action, but other challenges or other quadrant systems could have been envisaged. Even after quadrant selection, the attached narratives are not unique either. For instance, SSP1 ('sustainability') is a high-growth world selected to reflect low challenges to both mitigation and adaptation, but a different constellation of interests might have derived a low-growth, post-growth, or degrowth world instead. Similarly, in all SSP quadrants, it is possible to envisage alternative worlds that meet the criteria of these quadrants. The SSPs are not exhaustive either: the five narratives potentially miss relevant aspects (e.g., finance), emerging areas (e.g., artificial intelligence), or alternative economic paradigms (Walker Wood, Richter, & Atkins, 2024). Likewise, although a strong part of the SSP framework along the key dimension of 'challenges to adaptation', equity does not give a strong signal in SSP quantification (Kanitkar, Mythri, & Jayaraman, 2024; Skeie, Peters, Fuglestvedt, & Andrew, 2021). It is thus safe to argue that, like any similar scenario process, the SSP framework views the world through a specific, simplified reductionist lens and should not be viewed as a comprehensive view of the world.

2.3.1.3 Quantification: socioeconomics

The next step in the SSP process was to develop socioeconomic input data for model-scenario development. Based on the SSP narratives, different models were used to construct population (S. Kc & Lutz, 2017), urbanisation (Jiang & O'Neill, 2017), and economic data (Dellink, Chateau, Lanzi, & Magné, 2017), with analysts carefully interpreting the narratives and implementing the assumptions in their models. Since the SSPs span five alternative storylines, the quantified socioeconomic data illustrate five alternative pathways. It is not expected a priori that the socioeconomics would span all feasible socioeconomic solutions.

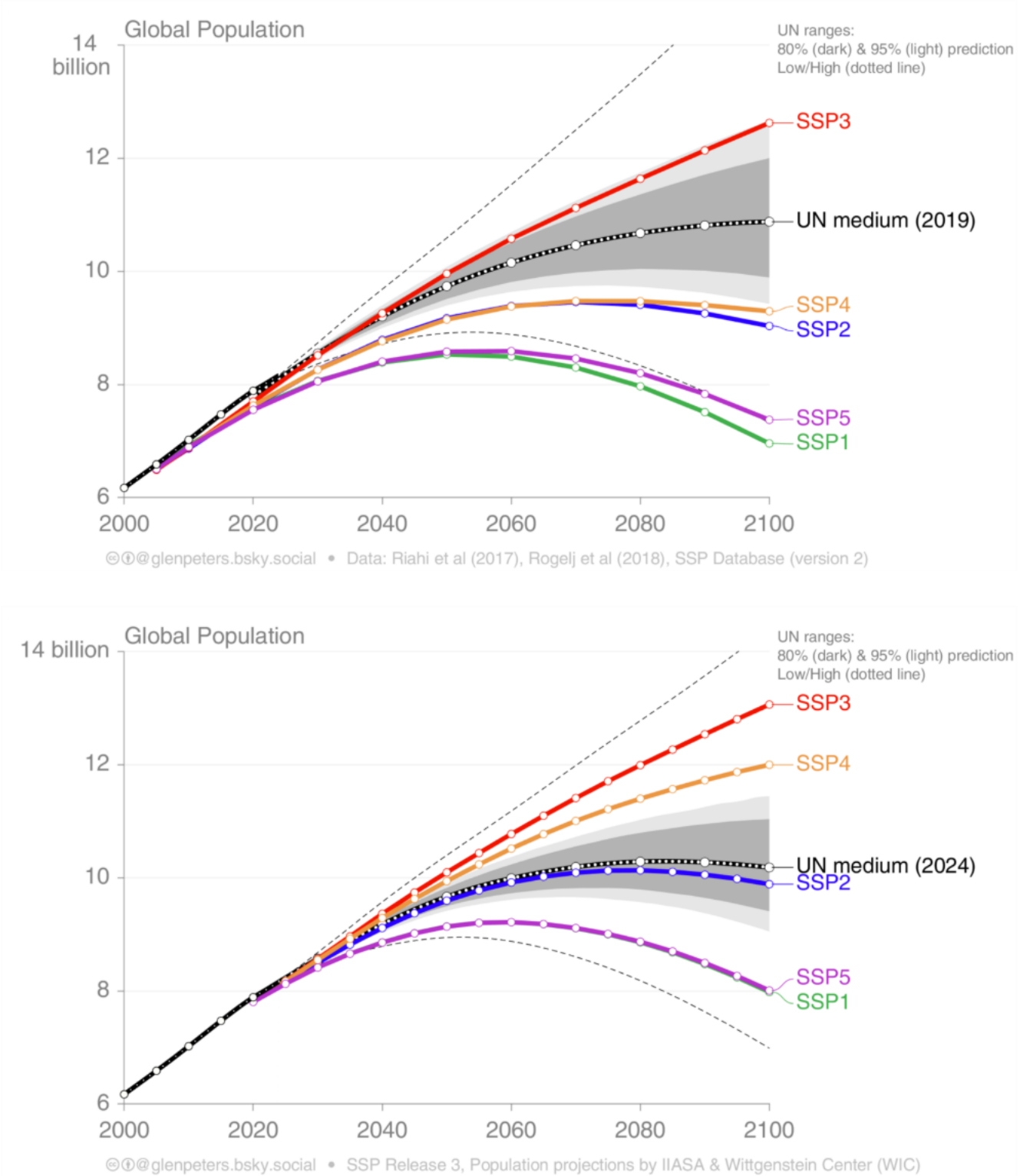


Figure 1. SSP population projections.

The upper panel shows data from the SSP Database version 2 and the UN Population Division for 2019, while the lower panel from the SSP Database version 3 and the UN Population Division for 2024.

Population projections based on probabilistic projections from the UN Population Division for 2019 (top) and 2024 (bottom), with median in solid black, the 80% and 95% ranges in shading, and the dotted lines for the low

and high sensitivity assessments, compared to the SSP Release 2 (S. Kc & Lutz, 2017) (top) and Release 3 (Samir Kc et al., 2024) (bottom).

The limited scope of the SSPs can be illustrated by comparing the population projections from the SSPs and the probabilistic population projections from the United Nations Population Division(Giarola et al., 2024). Two SSP versions are shown: Release 2 (Figure 1, top) and Release 3 (Figure 1, bottom). On the one hand, the SSPs are focused on addressing uncertainties across challenges to mitigation and adaptation and illustrating such uncertainties by means of the five scenarios; on the other, the UN performs a probabilistic projection around the median, looking at parametric uncertainties due to key variables. Therefore, the SSP and UN population projections have different motivations. SSPs (Release 2) clearly fall to the low side of the UN probabilistic range. Based on a comparison of these scenarios, one could argue that the SSPs (Release 2), as assessed in SR15 and AR6, have generally only explored the low end of population projections, particularly relative to the UN projections (Giarola et al., 2024).

The latest update (Release 3) in preparation for the IPCC Seventh Assessment Report (AR7) now displays similarity and a more even distribution around the UN projections (Figure 1, bottom). The revised SSP2 and latest UN median projection are now very similar, while a major revision to SSP4 population projections (nearly 3 billion additional people in 2100) helps make the SSP framework more evenly distributed relative to the UN projections. The significant shift in SSP4 serves to illustrate that the outcomes are dependent on assumptions such as high fertility rates due to low education levels in poorer nations, changing which can lead to large variations. This also illustrates that the scenarios in a database span only a part of the scenario literature ('ensemble of opportunity'), not the full range of the literature (which would inter alia include the UN projections), and further may not consider population uncertainties not expressed in the literature.

2.3.1.4 Quantification: energy and climate

The SSP-SPA-RCP architecture considers socioeconomics (SSP), policy (SPA), and impacts (RCP) as independent dimensions (van Vuuren et al., 2011). When quantifying the SSPs to produce energy and climate outcomes, modellers initially produce baseline scenarios without climate policy. To reach different RCPs, SPAs are added to the SSPs (Kriegler et al., 2014). The SSP narratives provide some additional information on the boundary conditions of the energy system (Bauer et al., 2017) (e.g., restrictions on the use of nuclear energy), but the mitigation outcomes are driven by the SPAs. The SPAs generally are globally harmonised carbon prices, but the SSP storylines allow for some flexibility in implementation (e.g., delayed implementation). Similarly, high-end scenarios with large climate impacts have zero impact on the socioeconomics or policy, per definition of the SSPs (O'Neill et al., 2020).

The general SSP concept is that different modelling groups can add policy and impact to the 'baseline' SSP. This arguably means the SSPs fail to meet criteria of coherency and internal consistency of the current IPCC scenario definition. This is easy to illustrate with some examples. Does it make sense for a highly fragmented world (e.g., SSP3) to have a globally harmonised carbon price? Can a fossil fuel-intensive world (e.g., SSP5) be consistent with strong climate policy and be devoid of climate impacts? Can a world striving for sustainability (e.g., SSP1) not have strong climate policy? These potential contradictions are hard to assess when treated as independent dimensions, and the model-scenario space could look quite different if interactions were assumed by default.

The scenario quantification process can serve many functionalities. It can help ensure coherence and internal consistency of the scenario narrative (Keppo et al., 2026; Schweizer & O'Neill, 2014). More practically, it provides a variety of scenarios for application in climate science (Riahi et al., 2017), and this is perhaps the most successful application of the SSP framework. A selection of the SSP-SPA-RCP combinations were used as input into Earth System Models (ESMs) in an activity known as ScenarioMIP – Model Intercomparison Project (O'Neill et al., 2016), with this selection of scenarios used extensively in IPCC AR6 WGI. In terms of mitigation, in IPCC AR6 WGIII, the

original SSPs were included in the scenario database but played a negligible role in the discussions throughout the Report.

The quantified SSPs were used to generate a matrix consisting of five SSPs and six RCPs, across six IAMs. Of the 180 possible SSP-RCP-IAM combinations, some were found infeasible (i.e., the IAM could not solve) while others were not attempted to begin with. Examples of scenario combinations found infeasible include reaching 1.9W/m2 in an unequal world (SSP4) or 8.5W/m2 without SSP5 socioeconomics. These findings could indicate that the scenario was not plausible, or that the employed IAM did not have sufficient flexibility to allow a solution at the time—other IAMs, or newer versions of the employed IAM, may find a solution depending on model development or expansion. Even if an IAM did find a solution, independent lines of evidence may find the scenario infeasible, such as high coal use in SSP5-85 (Ritchie & Dowlatabadi, 2017). Furthermore, the fact not all scenario combinations were attempted may indicate lack of resources or (subjective) expectation of infeasibility (see Table 2 in the Supporting Information of (Keywan Riahi et al., 2017). For those combinations that had feasible solutions (the model solved), results demonstrate how different socioeconomic assumptions (SSPs) lead to different energy systems and mitigation costs (Keywan Riahi et al., 2017; Rogelj et al., 2018).

The variation in primary energy across SSP-RCP combinations (Figure 2) identifies several robust findings across the six utilised IAMs. All primary energy pathways using SSP5 are higher than those in SSP1, regardless of the level of mitigation (RCP). The differentiation between the adaptation challenges (SSP3 vs. SSP5, SSP1 vs. SSP4) are less distinct than the differences across mitigation challenges (SSP1 vs. SSP5, SSP3 vs. SSP4). This demonstrates the important role that socioeconomics plays in dictating scenario (mitigation) outcomes, with those factors assessed for other outcomes like emissions, temperature, or mitigation costs (Al Khourdajie, Skea, & Green, 2024; Popp et al., 2017; Keywan Riahi et al., 2017). Mitigation analysis was a key application of the SSP framework, although the framework has arguably had a less notable impact elsewhere, such as adaptation research (Brian C. O'Neill et al., 2020), perhaps indicative of the smaller variations across the 'challenges to adaptation' axis.

2.3.2 SSPs and the model-scenario space

While the SSP framework has led to many achievements (Brian C. O'Neill et al., 2020), the original motivation was to facilitate a greater linkage across mitigation and adaptation research and speed up scenario generation (Moss et al., 2010). One could question how successful the process was on both criteria: modelling focus has predominantly remained on mitigation, while an assessment of how slower or faster the scenario generation process would have been without the SSP framework is not straightforward. Nevertheless, the SSP-RCP framework has been a key foundation of climate science. Complex ESMs are resource-intensive and can only run a selection of scenarios, of which ScenarioMIP provided (B. C. O'Neill et al., 2016), arguably making ScenarioMIP the most successful part of the SSP-RCP framework.

While the SSP-RCP based scenarios have extensive citation and use, that is because of their widespread adoption within the research communities feeding into IPCC WGI and WGIII assessments. The SSPs were an input in the IPCC Special Report on Global Warming of 1.5°C (SR15) but were barely mentioned in IPCC AR6 WGIII. Of the 126 scenarios from the original SSP exercise submitted to the AR6 scenario database, only 70 passed the 'vetting'. The IPCC states that "most of the scenarios in the AR6 database are SSP-based" (IPCC AR6 WGIII Box TS.5), but this is because most scenarios apply SSP2 baseline assumptions for socioeconomics (van de Ven et al., 2025). If correctly implemented, as in Keywan Riahi et al. (2017), each SSP would change a multitude of assumptions in a model, far beyond just switching between socioeconomics. This distinction is critical. It implies the scenarios utilising the SSPs do not, as one might assume, represent a broad exploration of different socioeconomic futures. Rather, it represents a deep exploration of one 'middle-of-the-road' future, making its statistical properties highly conditional on the SSP2 assumptions, and offering a very limited exploration of the model-scenario space for

different research questions.

2.3.3 Scenario databases

While it is common that individual scenarios are represented in some sort of database for practical reasons (e.g., analysis, plotting, etc.), a recent innovation in mitigation research lies in the compilation of scenarios from different studies into a single database (Peters et al., 2023). Based on voluntary submission, such 'ensembles of opportunity' are not an exhaustive attempt to compile all available scenarios. While not of a particular scenario design, databases form the basis of many scenario analyses and are, therefore, worth discussing explicitly given the numbers of studies utilising them. The AR6 scenario database was used for IPCC AR6 WGIII (K. Riahi et al., 2022), despite being unevenly representative of scenarios (Sognnaes & Peters, 2025).

Scenario databases are likely to span a limited part of the available scenario space and introduce a range of biases (Peters et al., 2023). In the global IPCC AR6 scenarios database, 919 unique scenarios were submitted from a total of 109 models (including versions), leading to 2,304 model-scenario combinations (not all models ran all scenarios). After adjusting for version numbers and hybrid versions, the models can be grouped into about 50 unique model families. After vetting and allocating a climate category, only 1,202 scenarios from 13 model families remain (Sognnaes & Peters, 2025)—297 scenarios came from one model (family), and 591 from one study(Keywan Riahi et al., 2021), while about 90% of the scenarios use SSP2 socioeconomic assumptions. Whilst not comprehensive, these statistics give a good indication of the uneven distribution of the AR6 scenario database, detailed elsewhere (Peters et al., 2023). Consequently, summary statistics used in IPCC AR6 WGIII SPM, for example, are directly influenced by this uneven distribution of models and scenarios, contesting the robustness of some of the findings (Sognnaes & Peters, 2025).

The quality of reporting of model outputs in a database also varies. Variability in data availability introduces challenges in asserting that these outputs collectively cover the model-scenario space (Sognnaes & Peters, 2025). Al Khourdajie, Skea, and Green (2024) examine what drives the differences in future energy scenarios, showing that a significant challenge emerges from missing data across model outputs. These reporting gaps create challenges for robust cross-model comparisons and make it harder to understand what truly drives variation in these variables. While it is feasible to require that modelling groups report more variables, this may reduce the model and scenario diversity in a database by raising the cost of entry, particularly to newcomers.

While pre-compiled scenario databases have distinct advantages (Peters et al., 2023), they also carry significant risks, many of which must be managed. Before presenting any statistical summaries, it is necessary to characterise the core properties of the database, particularly for what purposes the scenario database may be sufficiently representative. Database-level analysis should be a transparent and upfront part of the assessment, allowing readers to understand the specific 'slice' of the model-scenario space being analysed, and not a statistical analysis of a representation of the model-scenario-space.

2.3.4 Other scenarios

The Energy Modeling Forum (EMF) started in 1976 with an objective to bring together different energy-system modelling groups together to co-design research questions with decision-makers and answer the same policy-relevant and often-climate-related questions, in model inter-comparisons. To date, the EMF has completed 33 studies (with an additional four in progress), many of which feature their own databases and have been well referenced in IPCC assessments. The EMF has been highly influential in the modelling community (Cointe, Cassen, & Nadaï, 2019) and driving model intercomparison projects (Fujimori et al., 2025). While pushing forward scientific understanding through concerted efforts on model intercomparisons, it is only feasible to do so for selected research questions. These are no doubt relevant and topical at the time of

selection, but different stakeholders and research communities are likely to identify alternative research questions as most relevant.

In response to the demand for scenario-based climate risk assessments (TCFD, 2017) to inform financial institutions, the Network for Greening the Financial System (NGFS) scenarios have grown out of the research groups developing the SSPs—albeit based on different quadrants, spanning axes of transition and physical risks (NGFS, 2024). They are based exclusively on the SSP2 socioeconomics, suggesting that exploring different socioeconomic pathways was not prioritised in their implementation, although conceptually such exploration would be feasible. They comprise seven scenarios sitting in the different quadrants of the model-scenario space, with three in one quadrant alone (low physical risk, low transition risk). The multiple scenarios in a single quadrant essentially add more dimensions, representing different climate outcomes (e.g., 1.5/2°C) or policy approaches (e.g., low demand). Unsurprisingly, the NGFS scenarios are designed to address issues the network itself finds relevant and important, although those scenarios may not be relevant for other scenario users.

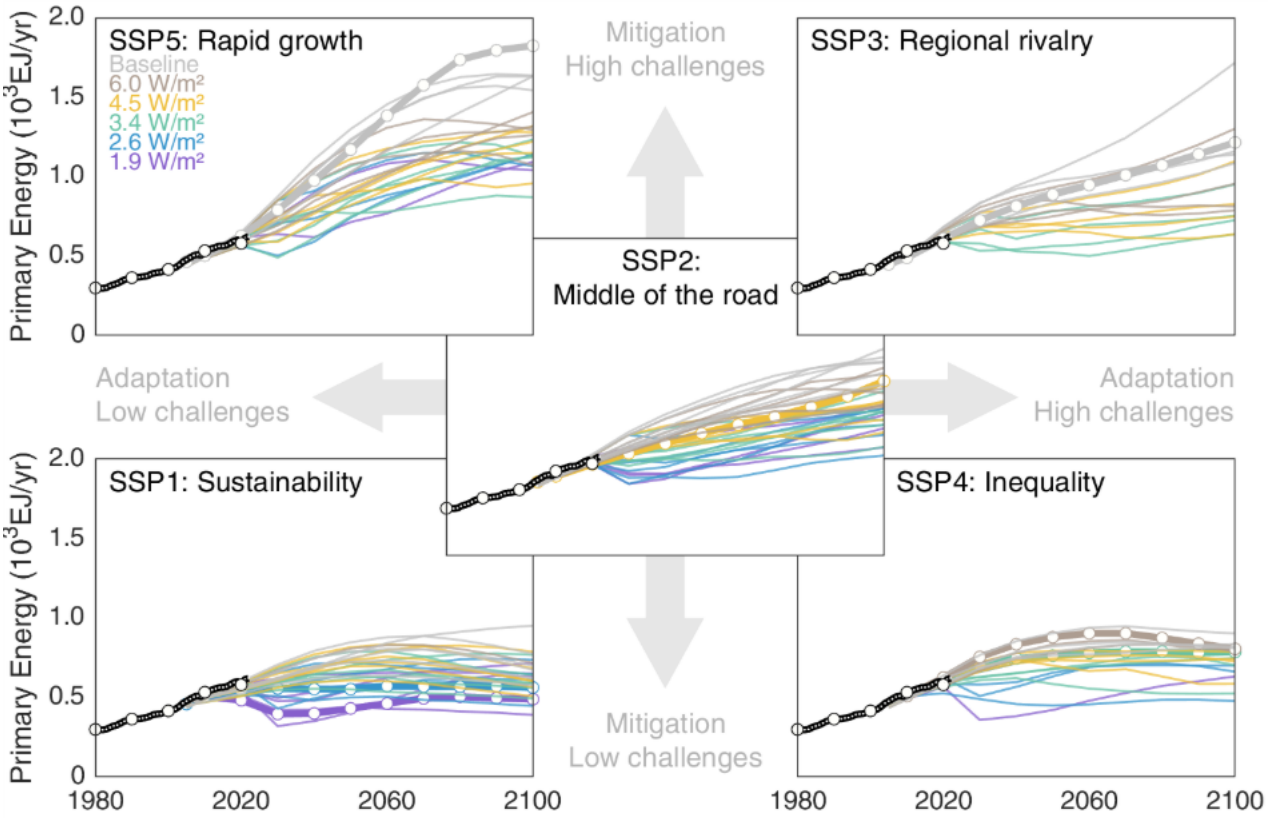


Figure 2. Primary energy in different SSP (boxes)-RCP (line colours) combinations

The SSP-RCP combinations placed on the SSP narrative axes of challenges to mitigation and challenges to adaptation, illustrating how primary energy evolves under different SSPs (boxes) and different SPAs (colours). Historical data is from the International Energy Agency (IEA) and the SSPs are from Riahi et al (2017) and Rogelj et al (2018), downloaded from the IIASA SSP Database Version 2.0. The International Energy Agency (IEA) also produces relevant scenarios. It only explores one socioeconomic dimension (outside the SSPs) but spans different policy storylines, In the latest World Energy Outlook, three scenarios were considered: Current Policies (CPS), Stated Policies (STEPS), and Net Zero Emissions in 2050 (NZE2050) (IEA, 2025). While their narratives are not as elaborate as the SSPs or SPAs, they still build around simple policy and technology narratives that then requires

quantification. The IEA uses one model framework to quantify these scenarios, but different modelling groups may get different answers, even if they harmonise assumptions (Sognnaes et al., 2021). The IEA policy scenarios are particularly important, not only due to the organisation's influence (Lahn et al., 2025), but because others often use them as the basis for their own scenarios. Many energy companies and other organisations also produce scenarios, each with their own narratives and context, even though many share similar elements to the IEA (Lahn et al., 2025; Skea, van Diemen, et al., 2021).

Finally, many other research groups develop scenarios relevant for climate mitigation, although not all groups are organised, thus their research usually appears in individual journal publications (Pereira et al., 2021) , grey literature (Skea, van Diemen, et al., 2021), or even on websites (Climate Interactive, n.d.). Many groups draw on the SSP framework but mainly to provide input baseline assumptions on population and GDP. Most literature will address specific research questions as outlined in their publications.

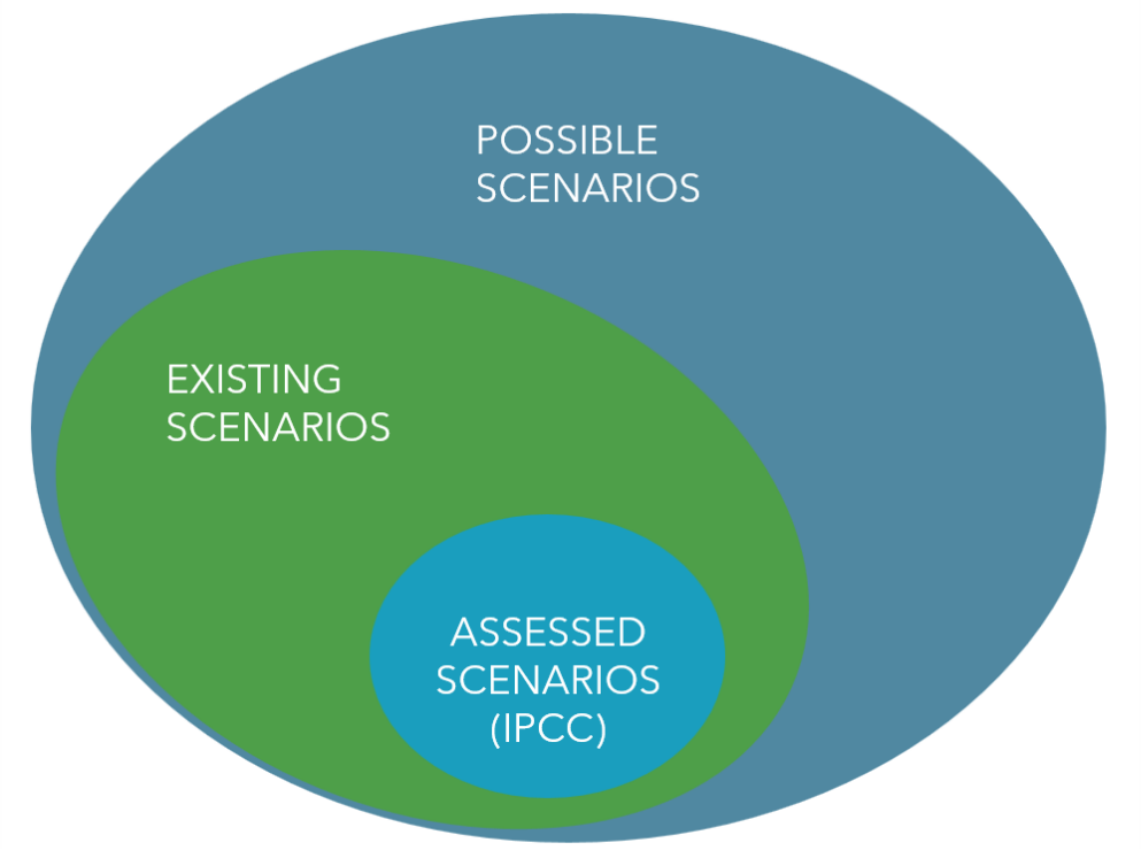


Figure 3. Hypothetical scenarios space of possible (dark blue), existing (green), and assessed by the IPCC (light blue) scenarios

A schematic of a hypothetical scenarios space of possible scenarios (dark blue). Within that space there are existing scenarios (green), and a subset of the existing scenarios are submitted to the AR6 scenarios database and assessed by the IPCC (light blue). The relative proportions of these areas are unknown, though the share of assessed scenarios in existing scenarios could feasibly be determined. The reality is far more complex, but this schematic is to demonstrate that the existing model-scenario space is limited in extent, and key dimensions are not fully explored.

2.3.5 The hypothetical model-scenario space

In practice, an infinite number of model-scenario combinations could be envisaged. We conceptually illustrate how this hypothetical 'model-scenario space' could be visualised (Figure 3, Table 1). Of all hypothetical scenarios, a subset may be published in academic or grey literature. These studies may come from multi-model

comparisons (using the same scenario protocol) or single-model studies. Scenarios from some communities not often working explicitly on climate may not be captured, particularly if they are alternative socioeconomic futures and visions of the future (Cork et al., 2023). Scenario databases, particularly those compiled in the context of IPCC assessments (Peters et al., 2023), are based on voluntary submissions and therefore cover a smaller subset of the literature. This serves to illustrate how the model-scenario space could be disaggregated. Perhaps the most interesting part of the model-scenario space is that which remains unexplored. Unexplored parts may be known or unknown (Table 1). Similar to the systematic 'multiple lines of evidence' approach used in AR6 WGI, WGIII assessments could have benefited from systematically integrating diverse model frameworks, qualitative scenario narratives, stakeholder perspectives, and empirical policy implementation evidence to strengthen the robustness of mitigation pathway assessments(IPCC, 2022b).

Table 1. Illustration of different scenario types in the hypothetical model scenario space.

Considered scenario type	Examples
Published and in the AR6 scenario database	Scenarios in the multi-model comparisons projects
Published and not in the AR6 scenario database	Not all modelling groups submit scenarios, e.g., limited scenarios from the IEA2
Scenarios that are minor variations to the published literature	Scenarios with variations in costs of key technologies or socioeconomics, e.g., existing models using UN population instead of SSP2, or using technology costs from different datasets
Scenarios that we know exist but have not been modelled (or modelled by very few models)	Scenarios that endogenously integrate climate impacts onto the land sector and affect CDR and its impact on mitigation pathways; Scenarios that assess the impact of AI on mitigation cost and power-sector transition; scenarios where climate impacts dominate and have significant feedbacks on socioeconomics; etc.
Scenarios that we do not yet know exist	100 years ago, it was unknown that computers would exist; futures we may view as highly unrealistic (unlimited cheap energy, space travel, etc.); alternatives to the SSP narratives; dystopian futures; etc.
Scenarios that are not using mainstream IAMs	Scenarios that do not use mainstream IAMs (e.g., agent-based models, systems dynamics, alternative economic paradigms, etc) may be difficult to submit due to alternative variables and definitions.
Qualitative scenarios	Scenarios exploring alternative futures but not quantified and therefore not amenable to inclusion in a numerical database.

Note: The first three rows are analogous to known-knowns, the fourth and fifth rows known-unknowns, and the final row is unknown-unknowns.

Funded by
the European Union

The hypothetical model-scenario space will never be fully populated or randomly sampled, and therefore great care is needed when assessing existing scenario databases, as their statistics cannot be considered representative of the full 'population' of possible futures (Guivarch et al., 2022). Even within the known model-scenario space (e.g., AR6 Scenario Database), it is important to point out the gaps. The IAMs or models used to generate scenarios, the variables (outputs) reported, and the associated analysis are also likely to be non-exhaustive. It is not clear how or whether one can define the boundaries of the model-scenario space that could usefully be explored by models, or how the coverage of the scenario database over such a space should be defined or quantified. The key conclusion remains that the hypothetical model-scenario space is unlikely to be randomly sampled, and thus statistics from the literature or scenario databases are unlikely to be representative of this space. While this is noted in both IPCC AR5 and AR6 scenario chapters, it has not yet been acted on.

2.3.6 Characterising the model-scenario space

For decision-making, it is important that we know the model-scenario space is sufficiently sampled for the given research question. How well, and what part of, the model-scenario space needs to be sampled depends on the research question. The global GHG emission reductions required to meet a given climate target may best be answered using one part of the model-scenario space, while an assessment of financial flows may require different models and a different part of the model-scenario space, if it exists (Alexandros Nikas, Frilingou, Al Khourdajie, & Gambhir, 2024). Some research questions may not require scenarios but build on physical science concepts like remaining carbon budgets (Peters, Andrew, Solomon, & Friedlingstein, 2015). Nevertheless, it is important to be able to characterise the model-scenario space to understand what sorts of research questions different samples may be able to answer.

We outline three broad ways to characterise the model-scenario space using literature review, quantitative analysis, and qualitative co-design methods. Conceptually, one could think of a taxonomy of scenario types and spaces. Our objective is not to limit the model-scenario space, but to better classify it. In doing so, we also prescribe a transdisciplinary approach to co-producing this space and its components.

2.3.7 Literature review

One way to identify missing parts of the model-scenario space is through literature review. There are several policy-relevant but underexplored areas, such as circular economy (Alexandros Nikas et al., 2022; Sovacool et al., 2020), land-based mitigation (Roe et al., 2019), climate finance (Hong, Karolyi, & Scheinkman, 2020), labour (Ram, Osorio-Aravena, Aghahosseini, Bogdanov, & Breyer, 2022), post-growth (Hickel et al., 2021) , extremes (McCollum et al., 2020), or behaviour (Hahnel, Chatelain, Conte, Piana, & Brosch, 2020). In many cases, models have not been capable of assessing many of the most pertinent issues and further model development is needed. Expanding models to address these issues gives them the capability of answering a wider range of research questions (Pye et al., 2021), albeit perhaps at the expense of increased complexity. While parts of the model-scenario space may not be fully elaborated, transdisciplinary processes and principles—including stakeholder engagement—can be used to co-create and refine the research questions to provide more relevant information within this space (Stephanie Briers & Vienni-Baptista, 2024).

While not exhaustive, literature review does give some indication to gaps in the scenario literature. A recent concern is the inadequately assessed and poorly implemented concept of equity (Kanitkar et al., 2024; Skeie et al., 2021) and its important implications (e.g., (Bauer et al., 2020; Muttitt, Price, Pye, & Welsby, 2023). The exclusion of climate impacts in scenarios is another contentious issue, which may make high-end scenarios (like SSP5-85) infeasible (Hausfather & Peters, 2020); including climate impacts in mitigation scenarios would change mitigation pathways and costs (Köberle et al., 2021). CDR dominance in scenarios has also been contentious (Anderson &

Peters, 2016; Fuss et al., 2014; van Vuuren, Hof, van Sluisveld, & Riahi, 2017): while some scenarios avoid large-scale CDR (van Vuuren et al., 2018) or CCS (Grubler et al., 2018), most scenarios remain at the high end of CDR feasibility levels (Grant, Hawkes, Mittal, & Gambhir, 2021). Policy and governance are poorly represented in scenarios (Bertram et al., 2024; Peng et al., 2021). Nearly all scenarios are dominated by the idealised implementation of global carbon pricing. While many current policy and NDC scenarios explicitly model real-world policies (Roelfsema et al., 2020; Sognnaes et al., 2021; van de Ven et al., 2023), extensions behind the current policy timeframe (often 2030) generally revert to standardised policy assumptions (Sognnaes et al., 2021). Relatively few scenarios model policies over longer timeframes (e.g., (Morris, Hone, Haigh, Sokolov, & Paltsev, 2023; van Soest et al., 2021). These examples illustrate areas where literature review has identified large scenario gaps.

2.3.8 Emerging quantitative methods

To supplement literature review, quantitative methods can help characterise the existing model-scenario space. To apply quantitative methods, the scenarios must be in a machine-readable format (e.g., in a scenario database). It is common to report various summary statistics, most notably percentiles (median, 25-75, 5-95), based on these databases. Summary statistics report what is in the database but, unless the database is a representative statistical sample of the wider model-scenario space, these statistics reveal little about the underlying statistical properties of the hypothetical model-scenario space. The dominant model or project is found to considerably change policy-relevant outcomes, with many key findings in the IPCC AR6 WGIII SPM more indicative of the dominant model than the underlying scenario dataset (Sognnaes & Peters, 2025).

There has been growing interest in classifying the model-scenario space using higher-level statistical and mathematical methods (Guivarch et al., 2022): Sobol decomposition(Dekker et al., 2023), clustering(Minx et al., 2024), regression trees(Achakulwisut et al., 2023), Shapley-Owen decomposition (Al Khourdajie et al., 2024), neutral networks (Li et al., 2025), etc. While these have advantages and disadvantages, they all share the weakness that they can only characterise the existing model-scenario space available in databases and not the hypothetical model-scenario space. Nevertheless, such approaches have synergies with literature reviews: by quantitatively exploring the characteristics of the existing model-scenario space, gaps in the literature can more easily be identified, allowing better overall quantification of parts of the model-scenario space that may be missing or poorly explored. Recent work has gone a step further by training deep-learning generative models on the AR6 scenario database to create tens of thousands of 'synthetic' pathways of selected mitigation indicators within seconds (Li et al., 2025). While computationally attractive, these neural networks inherit the structural and sampling biases of the training set and therefore interpolate, rather than genuinely explore, the model–scenario space. Therefore, such approaches risk reinforcing the same biases because they cannot invent features, regions, or relationships absent in the underlying ensemble (Al Khourdajie et al., 2024).

It is arguably becoming easier to generate large numbers of scenarios, through traditional modelling, generation of large scenario ensembles exploring the parameter space (Lamontagne et al., 2018) , and methods utilising different aspects of artificial intelligence (Li et al., 2025). However, these methods will be generally confined to the existing model-scenario space. Interpolation/extrapolation methods are unlikely to comprehensively cover all research questions. A Monte-Carlo analysis may produce thousands of pathways based on parameter uncertainty, but these will be limited by the scenario boundary conditions. Thus, with more scenarios and numerical methods being developed, the method of assessing the representativeness of scenarios, and performing robust assessments, will become increasingly challenging, and ultimately the assessment of scenarios may become its own research field, in contrast to scenario production and use.

2.3.9 Scenario co-design

Scenario processes are often driven by the interest of researchers and funding agencies, not necessarily by the needs of users or prevailing issues in society, risking a mismatch between scenario development and how scenarios support policymaking (Norström et al., 2020). This normativity along with the technoeconomic focus inherent in models have led to scholarship(Braunreiter, van Beek, Hajer, & van Vuuren, 2021) calling for rethinking modelling and model-scenario spaces in a participatory way toward increasing the imagination of what is desirable, plausible, and equitable in projected futures (Nikas et al., 2020).

Expanding the model-scenario space can be guided by key transdisciplinary principles (S. Briers & Vienni Baptista, Forthcoming), thereby diversifying who contributes to shaping the model-scenario space and with which goals and benefits. Some transdisciplinary principles paving the way to robust, inclusive scenarios are making scenarios much more contextually specific (Hoffmann, Deutsch, Klein, & O'Rourke, 2022), embracing plural perspectives (Vienni-Baptista, Fletcher, Lyall, & Pohl, 2022) in scenarios, and integrating these diverse knowledge and world views (Bornemann & Christen, 2020). This challenges the dominant scenarios with novel ones that embrace diverse perspectives sitting side by side (Bornemann & Christen, 2020) in a consolidated model-scenario space.

The process of designing scenarios alongside stakeholders (Lang et al., 2012; Lawrence, Williams, Nanz, & Renn, 2022) proposes a transformative shift towards reflexive research and inclusive stakeholder engagement to expand the model-scenario space. Co-design can follow a three-phase transdisciplinary process (a) familiarising with the problem space and all relevant actors (Stephanie Briers & Vienni-Baptista, 2024; S. Briers & Vienni Baptista, Forthcoming) and creating a joint understanding of the model-scenario space, its plural components, gaps and goals, towards addressing key limitations of traditional, expert-driven approaches to evidence-based policymaking (Herbig et al., forthcoming); (b) reaching consolidated reflections that redefine the model-scenario space in co-produced scenarios; and (c) legitimising and presenting scenario and model development derived from the expanded model-scenario space to policymakers. Such approaches take a step towards scenario development, assessment, and analysis that is societally relevant, rather than reproducing questions fitting neatly into existing scenario frameworks.

To ensure societal relevance and operability, inclusivity in the kinds of actors that are invited and able to contribute is a vital but challenging task (Herbig, 2024). A detailed process of actor familiarisation and engagement preparation is needed, reviewing who is overlooked and who is key to invite to formulate research questions driving scenario design. Although this takes time and commitment from all team members, with societal actors often needing to be personally engaged with and sometimes convinced of sharing their valuable knowledge, involvement of such actors can greatly benefit the expansion of the imaginable model-scenario space. Through involving diverse actors in scenario design, different needs and perspectives can be meaningfully included, rather than non-scientific actors merely validating scenarios embedded within a fairly fixed framework (Braunreiter et al., 2021).

2.3.10 Conclusions

We have demonstrated that the hypothetical model-scenario space is poorly characterised with the current generation of scenarios, and that we cannot know whether our current sampling approach using the literature or databases is sufficient to provide a meaningful representation (and statistical summaries) of the full model-scenario space. We expect this will remain the case in the future, as scenarios generally represent a contemporary snapshot of an ever-evolving research landscape. The current approach of using scenario databases for assessments means compiled scenarios answer very different research questions, not all scenarios in the literature are submitted, vetting and scenario selection may exclude certain modelling groups and scenarios, and some

research communities may not be motivated to submit scenarios (Peters et al., 2023). Consequently, the use of scenario databases must have strong criteria for scenario selection (Guivarch et al., 2022) to avoid conclusions heavily influenced by unrepresentative model-scenario distributions (Sognnaes & Peters, 2025).

One could wonder why the model-scenario space is so poorly explored, given the vibrant and influential modelling community (van Beek, Oomen, Hajer, Pelzer, & van Vuuren, 2022). First, constituting the most prominent line of evidence of the IPCC assessment, scenario databases pose various barriers to submission that might exclude certain types of modelling approaches or research communities (Peters et al., 2023). Second, arguably, much of the (financial) support for modelling and scenario development falls to bigger, organised research groups (Cointe et al., 2019). Ensuring greater diversity in the research questions asked and the scenario methods used to answer them will likely require lowering the entrance barriers for new participants and give them stronger incentives to contribute. Nevertheless, even with broad participation from diverse communities, the scenario literature (and databases) will continue to be dominated by questions relevant to the teams developing scenarios, rather than to the wider (policy) community.

We argue it is necessary to refocus scenario assessments around key research questions co-produced with heterogeneous research communities and stakeholders. It is the research questions that should determine socioeconomic assumptions, model selection, vetting criteria, and ultimately scenario selection. While individual studies will address specific research questions, the collection of these studies into a database cannot give answers to an identifiable and meaningful research question, rather a mosaic of scenarios addressing different issues.

Building on the IS92 assessment (IPCC, 1994), we suggest revisiting the purpose of scenarios and the criteria they should meet to address specific research questions. While compiling scenarios into a database has merit (Peters et al., 2023), the nature of the database makes it increasingly important to select scenarios for specific questions (Guivarch et al., 2022). More prominent linking of the scenarios in a database to explicit research questions, through metadata, could be helpful in this regard.

While scenarios have had an influential role in the IPCC context (Pedersen et al., 2021; van Beek et al., 2022) , there have seemingly been few attempts to gauge how scenarios are used(Lahn et al., 2025). There remains potential, however, to better mobilise users to help frame the research questions, and thereby the tools and methods used to address those questions (Briers & Vienni-Baptista, 2024). We recommend a much more concerted effort to determine how scenarios are used, or how they may or may not influence decisions, and to identify what types of scenario analysis will be most useful to stakeholders in the future.

More emphasis must be placed on how to assess scenario 'ensembles of opportunity'. It is increasingly easy to access scenario information via databases and run standardised quantitative analysis from open-source software packages. However, basic approaches to assess the representativeness of the sample and the robustness of answers to that sampling is generally missing. While powerful and influential to have succinct messages on the desired emission or fossil fuel reductions for given climate outcomes highlighted in IPCC reports, these may be misleading if the statistical sample is not representative of the underlying uncertainty space (Sognnaes & Peters, 2025). The development of assessment guidelines for scenarios would be a useful first step to ensure robust assessment of scenarios. Further, drawing on alternative and diverse methods, would help build multiple lines of evidence, strengthening the robustness of key scenario findings.

Funded by
the European Union

3 Climate assessment and a climate assessment pipeline

3.1 Introduction: Summary of climate assessment trade-offs

Integrated assessment models and similar emissions-focused models typically model greenhouse gas emissions and some set of the underlying socioeconomic and technoeconomic drivers, but not global temperature or other climatological variables that are impacted by the emissions. To calculate the climate implications of the scenarios, a separate set of tools is usually used to estimate average global temperatures or other climatological responses based on the emissions, here referred to as "climate assessment" (Peters et al., 2023).

Methods to estimate global temperatures from emissions can range from simple and non-demanding but crude methods like simply multiplying cumulative CO_2 emissions by an estimated value for the transient climate response to cumulative emissions of CO_2 (TCRE), to full climate modelling that takes into account all emission species and their time-dependence and which yields a rich set of time-dependent climatological variables but is far more demanding in terms of both the number of greenhouse gas emission species that must be modelled and in terms of computational resources.

Cruder methods such as multiplying by TCRE are necessarily less precise, given that they disregard many emissions species and possibly other factors that are relevant for the temperature response, in favour of using measured or computed correlations between warming and a single or small number of emission-based quantities. When assessing a number of different scenarios from different studies based on different assumptions, one also faces the challenge that different studies may have assumed different historical values for the emissions and different values for costs, efficiencies or other parameters that link emissions to underlying drivers. This means both that scenarios with similar narratives might end up with different temperature responses due to differences that are not related to the scenario logic. It may also cause inaccuracies in the temperature estimation itself, if it is based on correlations between temperature and emissions in scenarios that have a different starting point for the emissions, such as is the case for infilling of missing emission species (see below).

More precise methods that use climate models to calculate climatological responses, on the other hand, can be more precise, but are typically more computationally expensive than cruder methods, even when using simple climate models rather than complex earth system models. And most notably, they may exclude scenarios and models that don't provide a sufficiently complete set of emission species.

In the context of the IPCC's Working Group III (WGIII) and related reports that made use of ensembles of IAM scenarios, simple climate models have been used to perform climate assessment based on modelled emissions with an increasing degree of standardisation. The latest iteration in the 6th Assessment Report (AR6) followed a "pipeline" of vetting (filtering out divergent scenarios), harmonisation (adjusting emissions to fit a chosen historical level) and infilling (adding missing emission species required for climate modelling), before running simple climate models to compute climate responses.

Each of these steps addresses one or more challenges caused by using climate modelling instead of cruder approaches but introduces challenges of its own. In particular, the infilling step makes it possible to provide a climate assessment for models outside of the small set of models that represent all emission species that the simple climate models require. But in so doing, it makes the emission trajectory of those species dependent on assumptions or dynamics in other models that may not reflect the dynamics of the assessed scenario itself. This introduces an uncertainty similar to that of just multiplying cumulative CO2 emissions by TCRE, in nature If not in magnitude.

In Deliverable D5.1 Section 2, we had provided a detailed description of each step in a typical climate assessment

pipeline modelled after the one used in IPCC AR6 WGIII and enumerated the various choices to be made and uncertainties that are inherent in each of the steps. We will not repeat or elaborate further on most of that discussion here but will report on completed and ongoing work on multiple methods for climate assessment of the modelled scenarios in DIAMOND WP5, and additional general points related to climate assessment pipelines that were not discussed in D5.1.

3.2 Role of infilling, and harmonisation and vetting as enablers

Deliverable D5.1 discussed the purpose and the issues to consider for each step in the scenario assessment pipeline, including vetting and harmonisation as well as infilling. An important point that was perhaps not stated clearly enough there, is that in a pipeline with vetting, harmonisation and infilling, vetting and harmonisation are not just for removing "unrealistic" scenarios and improving comparability between scenarios, but are also important for ensuring that the subsequent step in the climate assessment pipeline does not produce inappropriate results.

We elaborate briefly on this point here, since it is relevant for the considerations that are made when designing climate assessment procedure for the DIAMOND scenarios.

3.2.1 Harmonisation as a requirement for safe infilling

In D5.1, we provided an extensive discussion of the different choices to be made when harmonising emissions. We mainly highlighted harmonisation as a tool to ensure comparability of results across scenarios, and a common starting point for all scenarios.

However, harmonisation is also crucial for any analyses that use correlations between emission species or between emissions and some other variables in an ensemble of scenarios. Such analyses include both the infilling step in the conventional, and most of the alternative methods that we explore in Section 3.3. If the emission figures in the scenarios used to derive correlations are not consistent with the emissions in scenario those correlations are being applied to, the result may be skewed or misleading. Similarly, if the emissions in the ensemble are not consistent with each other, the computed correlations and any analyses based on them may be faulty as well.

The harmonisation is therefore a necessary step in pipelines that include either an infilling step, or any steps where emissions in one scenario are being indirectly or directly compared to emissions in other scenarios.

3.2.2 Vetting as a requirement for safe harmonisation

In D5.1 we also extensively discussed the use of vetting criteria in the IPCC AR6 WGIII climate assessment to exclude scenarios from assessment if some key emission figures in a given historical year were too far from observed historical values. We there commented that vetting criteria could be important for selecting only scenarios that are appropriate for elucidating a given research question, while also stressing that vetting criteria should be tailored to the research question at hand, and cautioning against blanket vetting criteria that might deprive some classes of scenarios of attention even though they might be useful for answering certain important types of research questions.

But in the context of a climate assessment pipeline, vetting is also important to guard against problems that harmonisation might introduce, and therefore for the "safe" use of the pipeline as a whole. The main problem with harmonisation is that it shifts entire emission trajectories up or down based on mismatches with historical data in a single historical year. If the new emission levels in future years are not actually appropriate for the energy use, mitigation effort or other properties of the assessed scenario, and is large enough to significantly shift the assessed temperature relative to what one might expect from the scenario logic, the results might imply an inaccurate

relationship between warming levels and other scenario properties such as technology deployments, mitigation costs, etc.

The risk of such harmonisation-induced artefacts will be small if the emission shifts caused by harmonisation are modest and unlikely to significantly affect the temperature outcome. But this can only be guaranteed if the emissions in the assessed scenario are not too far from the historical emissions to begin with. As such, imposing vetting criteria that require key emissions to be close to historical values can be essential to prevent the harmonisation and subsequent infilling step from affecting the assessed temperature and later post-analyses too much. However, this does not necessarily justify vetting non-emission variables that are not harmonised, such as energy production from specific sources. For example, the IPCC AR6 climate assessment pipeline imposed vetting criteria on electricity production from nuclear, solar and wind in 2020, which turned out to be the most exclusionary criteria (Kikstra et al., 2022).

3.2.3 Limited impact of harmonisation and infilling given vetting criteria

The vetting criteria used in AR6 included that fossil CO_2 emissions could not deviate from a given level in 2019 by more than 20%, and total CO_2 emissions not more than 40%. Especially the latter may not seem like a strict criterion. But given that the scaling done by harmonisation in the basis year (2015) was reduced linearly over time to 0 in 2080, the impact on cumulative emissions is just half of that on average, over 65 years. This would be an absolute maximum impact on cumulative emissions of 575 Gt CO_2.

A very simple estimate of temperature impact by multiplying this with an estimated TCRE of 0.4 C/TtCO_2 yields an impact of 0.23 C, which is not insignificant. But given that the constraint on the fossil part of CO_2 emissions is only half as much (20%), and that emissions and therefore the absolute impact of the harmonisation goes down over time for many scenarios, the actual temperature impact of harmonisation will be much less than this for most scenarios that pass vetting. This was also pointed out already by Kikstra et al. (2022), who found a very limited impact on the most important emission species for the scenarios that passed vetting.

3.3 Alternative climate assessment methods for DIAMOND

3.3.1 The case for alternatives to the climate assessment pipeline

This section will discuss approaches to assess the temperature responses for the DIAMOND baseline scenarios (see Section 4), some of which have been carried out some of which are still in progress.

Deliverable D5.1 discussed at length the climate assessment pipeline based on harmonising and (if needed) infilling emissions, followed by running the resulting emissions through a simplified climate model. These steps are relatively computationally costly, in particular the final climate modelling step. The infilling step further makes the outcome dependent on correlations between emission species in the scenarios that are included in the infiller database, even if it is not guaranteed that the same correlations should logically be present in the scenario that is being assessed.

In DIAMOND, most models do not model all the species required for a direct climate assessment. In addition, some models and scenarios are run only to 2050 rather than to 2100, which means that direct climate modelling could compute warming levels and other climate variables only to 2050. This a problem both because many climate targets are formulated for 2100, and because the short time left to 2050 means that most scenarios have not had time to develop a clear gap in temperatures even if the scenarios have quite divergent emission trajectories. To make an assessment of climate response to 2100, it is therefore necessary either to infill missing *years* from 2050 to 2100 (i.e., extend the emissions trajectories) in addition to infilling missing species, or to use

methods that don't rely on complete emission trajectories at all.

In DIAMOND, we have the benefit of having access to more than 1200 scenarios that were formally climate-assessed for the WGIII report in IPCC AR6, 500 more that did not pass vetting criteria but could nevertheless be run through SCMs and received a temperature estimate, as well as many more scenarios being assessed by the Scenario Compass Initiative (Huppmann, 2026) and other studies. This means that climate assessment can utilize not just correlations between emission species like the infilling step does in the traditional pipeline, but also correlations between emission variables or other drivers, and the temperature outcomes themselves.

Some of the methods below rely on these existing assessments of other scenarios to infer temperature responses for the DIAMOND scenarios or other new scenarios. As such, they are not new methods that can be used to do climate assessments from scratch with no pre-existing climate model runs, but a way of using existing runs as "training" data to assess additional scenarios using less computational effort.

It should be noted that, as for infilling, the results from any climate assessment method that uses the correlations in existing scenario databases will carry a statistical imprint from those databases. This is unavoidable when trying to assess the climate outcomes from scenarios that do not have all required emission species and/or years, as information about those missing emissions and/or years must be inferred from some other source or simply assumed. This in turn creates an unavoidable risk that both the estimated temperature response and any uncertainty estimates will be misleading if the narrative or model dynamics in the scenarios to be assessed are outside of the space spanned by the scenarios in the scenario database. The purpose of exploring alternative methods for climate assessment is not to avoid these unavoidable biases. Rather, it is to explore the effect of using alternative methods in itself, and to find ways to reduce the computational effort required to do climate assessment of new scenarios. Reducing the computational resources required can in turn make it possible to probe biases and sensitivity better, by allowing additional assessments to be made with alternative databases or by varying other input parameters.

Of the approaches listed below, the "temperature sandwich" method is the only one for which an assessment of scenarios produced in DIAMOND has been completed at the time of writing, while the others are in progress. For the other methods, we therefore describe and discuss the methodology rather than present completed results.

All of the following methods except "outer-bounds infilling" rely on having a pre-existing ensemble of scenarios that have already been climate-assessed through regular climate modelling or other independent methods, and that provide data for all required years. This ensemble will for simplicity be referred to as the "scenario database" below (not to be confused with any databases of scenarios that have been modelled in DIAMOND or in the project where the methods are being applied). The scenario or scenarios that are being climate-assessed using the methods will be referred to as the "assessed scenario(s)".

3.3.2 Cumulative-emissions constraints: The "temperature sandwich" method

The temperature increase induced by anthropogenic greenhouse gas emissions is strongly correlated with and nearly proportional to cumulative CO_2 emissions, (Matthews, Gillett, Stott, & Zickfeld, 2009) with a smaller variable contribution from other climate forcers and internal climate-system variability. This fact is used in the simplistic approach of estimating temperature increase by simply multiplying cumulative CO_2 emissions by TCRE. But given a database of already assessed scenarios, it can also be used to constrain a time-dependent range for the full temperature trajectory, with a span that reflects the variability in the database as a crude measure of uncertainty.

The method starts by defining two disjoint subsets of scenarios from the scenario database for each assessed scenario:

1. A "higher" group: All scenarios whose cumulative CO_2 emissions are higher than the cumulative CO_2 emissions of the assessed scenario in every model year after an appropriately selected start year. This represents scenarios that *should* have higher temperatures than the assessed scenario. Some scenarios however may still have somewhat lower temperatures due to differences in other emissions or other climate forcers.
2. A "lower" group: All scenarios whose cumulative CO_2 emissions are similarly *lower* than the assessed scenario. In the same way as the high group, these scenarios should in most cases have lower temperatures than the assessed scenario, but some may have somewhat higher temperatures for similar reasoning.

We can then initially estimate a time-dependent range of likely temperatures for the assessed scenario as follows:

1. Define the *lower* limit of the range for each year as being the *minimum* temperature in that year across scenarios in the *higher* group. This lower limit answers the question "how low can temperatures be in scenarios that should have *higher* temperatures based on CO_2 emissions alone?".
2. Define similarly the *upper* limit for each year as the *maximum* temperature in that year across scenarios in the *lower* group. This similarly answers "how *high* can temperatures get in scenarios that should have *lower* temperatures based on CO_2 emissions alone?"

If the climate modelling used to construct the scenario database provided temperature distributions or warming probabilities for each database scenario, the "temperature" in the points above should be taken to be the median temperature for each database scenario and year.

For both limits, it may be necessary to not use the actual maximum and minimum temperature, but rather, e.g., the 95th and 5th percentiles across the lower and higher groups, to avoid outliers. Determining an appropriate percentile will require some manual tweaking, such as varying the percentile and seeing at what point the temperatures suddenly jump quickly down or up to unrealistic-looking values.

This procedure yields a moving temperature range that the assessed scenario is very likely to stay within, assuming that the assessed scenario is not far outside the region of scenario space that is spanned by the scenario database.

If a simple range like this is sufficient for the analyses one has in mind, the method can stop here. If one needs more information about what goes on inside that interval, or additional ranges that reflect the climate-model warming probabilities in the database, one needs to extend the method to select a set of scenarios that can provide this information.

Such scenarios can be selected by choosing all scenarios from the scenario database whose median temperature for each year lies inside the range. These scenarios can then be used for things like defining a central temperature trajectory by taking the median temperature across the selected scenarios for each year, or to define extended temperature ranges that reflect the temperature distributions from the climate model by, e.g., taking the minimum of the 33rd percentile and the maximum of the 67th percentile warming level across the selected scenarios for each year.

Note that this method will fail or produce a skewed range if the CO_2 emissions in the assessed scenario and those in the scenarios of the infilling database don't start at close to the same level in some base year. It is therefore necessary to either have an assessed scenario and a scenario database where CO_2 emissions have been harmonised to the same base year. If this is not the case, a minimalistic harmonisation can be done by simply scaling either the assessed scenario to match the database scenarios, if they have been harmonised in a given base year (as is the case with the IPCC AR6 WGIII database, for 2015), or by scaling each of the database scenarios to match the assessed scenario in a suitably chosen base year.

This procedure was applied to the baseline scenarios in DIAMOND (see Section 4), using all temperature-assessed scenarios from the IPCC AR6 Working Group III database as the scenario database. The resulting temperature trajectories and ranges (both the initial range and climate-modelling uncertainty ranges) are shown in Figure 4 and the CO_2 emissions (per year) of the selected database scenarios are sown in Figure 5. Only OPEN-PROM was run to 2100, while the other models only ran to 2050. The figures give an instructive visualisation of the effect of including additional years: The initial temperature range for OPEN-PROM (the inner blue range) is quite narrow, since the full time series limits exclude a lot of scenarios that fall little or fall extremely steeply in the second half of the century. The other models leave room for a much more diverging set of trajectories after 2050 and have correspondingly wider ranges that fan out considerably after 2050.

The diverging ranges for the scenarios that stop in 2050 also offers a lesson for any scenario that only provides data to mid-century but tries to estimate warming to 2100, a common occurrence, e.g., in the world of corporate energy scenarios: The outcome in 2100 turns out to be strongly affected by what happens after the end of the scenario. Furthermore, if the scenarios from the IPCC AR6 database are used to extend or infill the assessed scenario, many of those scenarios have large emission reductions after 2050 even in the case of very modest reductions before 2050. This means that the resulting temperature assessment requires quite ambitious emission reductions after the end of the assessed scenario, which may require much greater mitigation efforts after 2050 than the assessed scenario itself assumed up to 2050.

An advantage of this approach is that it only requires CO_2 emissions to be modelled, and that it automatically gives a range of possible extensions to the last database year (i.e., 2100 for the AR6 database) for models that only run over a shorter period. If the assessed scenario only provides fossil CO_2 emissions without land-use change emissions, or only energy-related CO_2 emissions without industrial processes, the method can still be used by simply comparing with the same subset of CO_2 emissions in the database scenarios, although may produce broader temperature ranges.

A drawback is that the approach disregards other species if they are available, although this could be mitigated by changing the scenario selection criteria to also require that emissions of some or all of the other species be within some maximum distance from the model results for each species and each modelled year. Another drawback is that if the scenario being assessed has a CO_2 emission trajectory shape that is very different from most scenarios in the database, the initial range may end up being undefined, since the higher and lower groups may be so far from each other that their temperature ranges do not overlap. Or for the subsequent scenario selection step, the scenario selection algorithm may pick out very few scenarios from the database or possibly none at all. That would either fail to produce a median temperature trajectory at all or would produce a trajectory with an artificially narrow range and a level and shape that are very strongly biased by the peculiars of the few database scenarios that are selected. However, scenarios with emission trajectories that are very different from all scenarios in the database will also create challenges for most infilling methods, regression methods and indeed most other correlation-based methods as well, so this drawback is by no means unique to the "temperature sandwich" method.

Funded by
the European Union

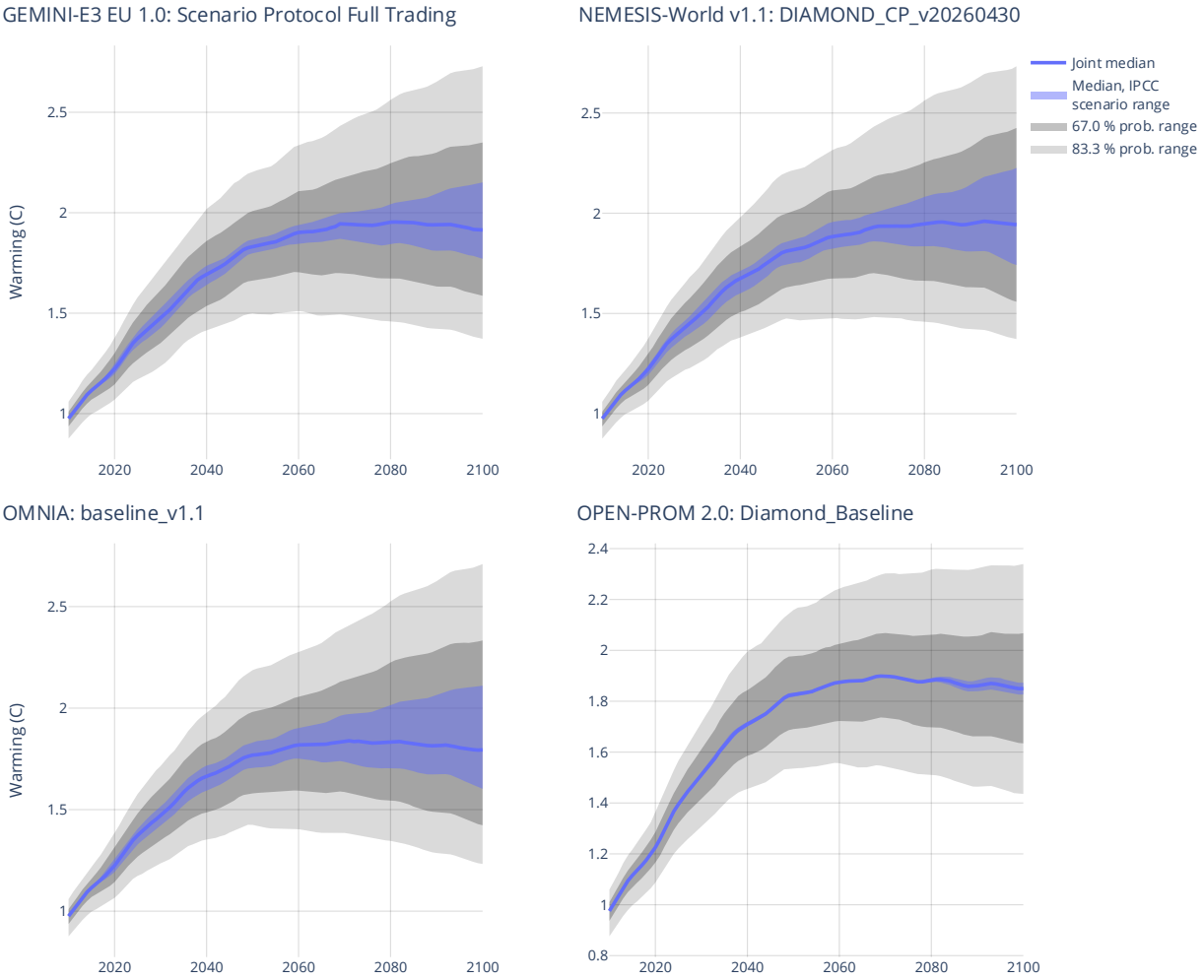


Figure 4. Temperature trajectories and ranges estimated using the "temperature sandwich" approach

Note: Temperature trajectories and ranges estimated using the "temperature sandwich" approach for baseline scenarios in DIAMOND. The blue line is the median of selected database scenarios (IPCC AR6 Working Group III database). The blue range represents the “sandwiched” range used to define the temperature range and scenario selection. The outer grey ranges are the maximum and minimum limits for corresponding percentile warming levels across the selected database scenarios, which represents climate model-related uncertainty. The initial sandwich range was constructed by taking the 2.5th percentile and 97.5th percentile of the temperature across the higher and lower groups, respectively.

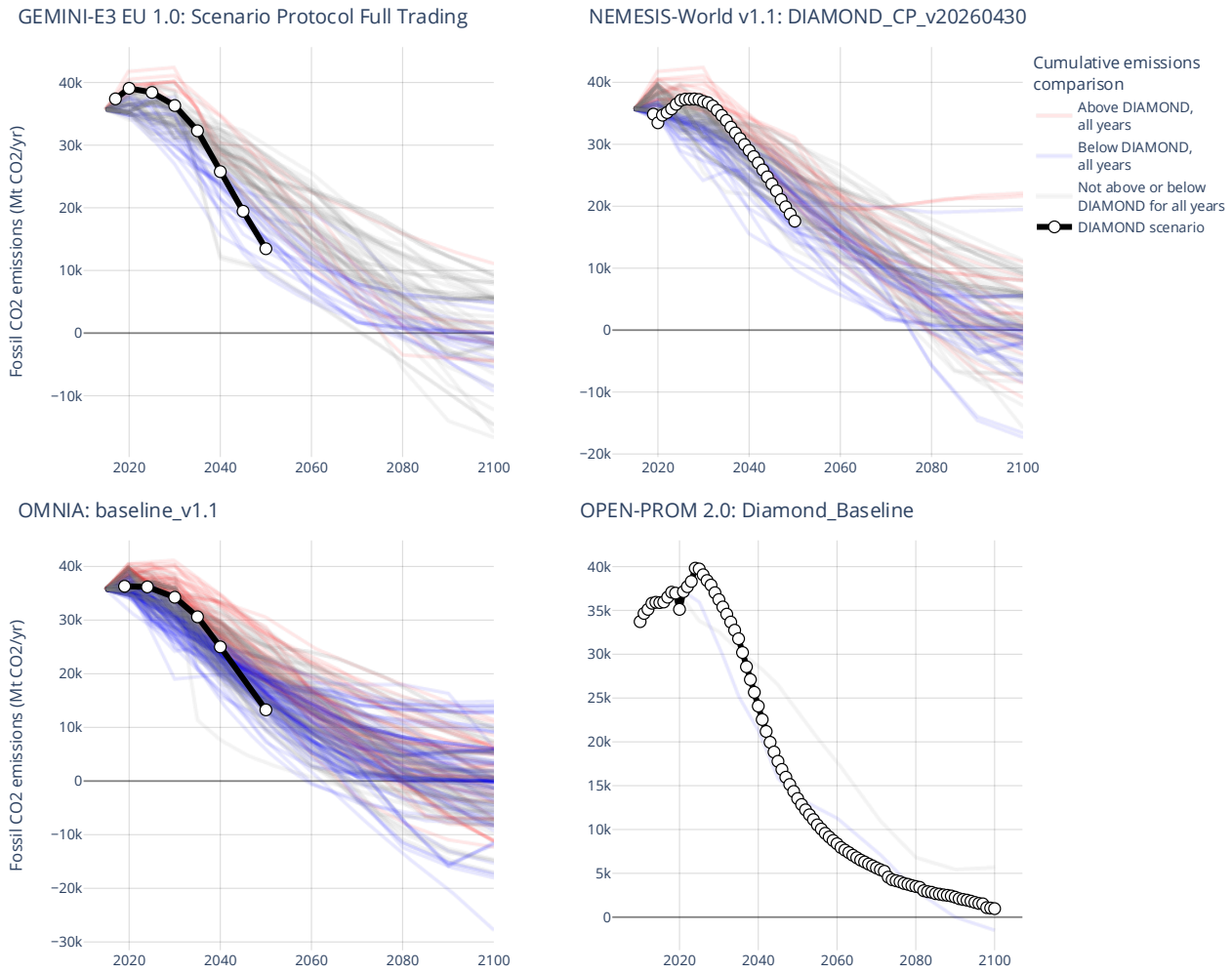


Figure 5. CO_2 emission trajectories for the DIAMOND baseline scenarios

Note: CO_2 emission trajectories for the DIAMOND baseline scenarios and the database scenarios selected by the "temperature sandwich" algorithm. The blue and red trajectories are database scenarios that have lower and higher cumulative CO2 emissions, respectively, than the assessed DIAMOND scenario. Cumulative emissions were compared from 2025 onwards to avoid that small differences in the initial years would exclude a large number of scenarios. The grey trajectories are additional scenarios that are inside the initial temperature range and therefore selected in the scenario selection algorithm, but whose cumulative emissions are not consistently lower or higher than the assessed scenario in every year (i.e., the cumulative emissions are initially higher or lower than in the assessed scenario, but cross the assessed scenario one or more times).

The methods in the following subsections are still in the process of being tested with the given assessment methods. We therefore do not report results for these methods, but explain each method, along with some considerations of choices to be made, advantages and drawbacks.

3.3.3 Direct infilling: Skipping the climate-modelling step

In a conventional climate-assessment pipeline, infilling is usually used to add missing emission species to a assessed scenario, by constructing emission trajectories for the missing species based on their trajectories in one or more database scenarios that are selected by matching on the trajectory of an emission species that is provided in both the assessed scenario and the database scenarios, often referred to as the "lead variable". The assumption is that there is some logical correlation—direct or indirect—between the time evolution of the lead variable and the missing species, and that this corelation holds to some extent in both the assessed scenario and the database scenarios.

If one makes this assumption, one can in principle also infill any other variable that is present in the database and for which one can that a correlation exists with a lead variable that is modelled in the assessed scenario. In particular, temperature and most other climate response variables *are* correlated with CO2 emissions. One can therefore use the exact same infilling procedure as is used to infill emissions to instead infill temperature and other climate variables and skip the climate modelling step entirely. Some infilling methods also support using more than one lead variable, and this could be done to match on more species than just CO2 if the assessed scenario provides additional species.

One great advantage of this method, apart from avoiding the computational cost of the climate modelling step, is that it is simple and flexible. It can for example be tailored by, e.g., including only scenarios that fit certain similarity criteria in the scenario database, thereby avoiding matches on scenarios that have similar trajectories for CO_2 emissions (or other lead variables if applicable) but are very dissimilar in other, known ways.

The main drawback relative to the conventional approach of infilling emissions and then running a climate model, is that since the lead variable is used to infill temperature directly rather than running a full set of emissions through a climate model, the method implicitly transfers correlations between *all* emission species from the matched database scenario(s) to the assessed scenario, not just the correlations between the lead variable and the infilled species. In the conventional approach, if an assessed model models some non-CO_2 species natively, these species are not affected by the infilling, and the emissions that are input into the climate model can therefore be an independent mix of natively-modelled non-CO_2 species and infilled species, but this independence is not maintained in the "direct infilling" approach. Unlike the "temperature sandwich" approach, this approach also does not give any measure of the range of emissions in database scenarios that might be close to the assessed scenario, but not close enough to be the ones that are selected for the infilling. It therefore does not give as much information about potential uncertainty as the temperature sandwich method does.

3.3.4 Time-series regression: PCA on time-dependent, correlated emissions

The "direct infilling" approach uses the same methodology as the infilling in the conventional climate assessment pipeline, but changes which variables are infilled into the assessed scenario. There are several different concrete methods that can be used to select scenarios from the database and derive values to infill from them (so-called "crunchers" in the language of SILICONE, a widely used infilling library), but they can all be thought of as particular forms of regression (Lamboll, Nicholls, Kikstra, Meinshausen, & Rogelj, 2020).

The approach can be generalised by using alternative regression types to derive temperature and other climate variable values from the scenario data in the scenario database. By using multivariate regression methods, the approach can be made to take any or all modelled emission species in the assessed scenario into account, not just CO_2.

Each assessed scenario usually consists of a large number of variables, each of which provides values for a number of different time steps rather than a single variable value, and which can be both highly correlated with each other and autocorrelated across different time steps. Suitable regression methods therefore need to be able both to use time-series as regressors and correlation between regressor variables.

One approach that we are currently testing, is to decompose the variables into empirical orthogonal functions (EOFs) to obtain a set of basis timeseries that are not linearly correlated, (Hannachi, Finke, & Trendafilov, 2022) and then performing a regression analysis using the EOFs that have the highest linear correlation with the temperature variable in the scenario database (the same approach can also be used with other climate variables of interest).

EOFs are basis functions that are the result of performing principal component analysis (PCA) on timeseries

variables. The scenarios are treated as that are derived by treating the scenarios as vectors in an N×V-dimensional vector space, where N is the number of timesteps and a V is the number of variables included in the analysis. I.e., an element in the vector space is defined by a value for each variable at each timestep. The linear correlation matrix between the values of each included variable at each timestep is then a matrix in this vector space. EOFs are then found as the set of basis functions that diagonalise this matrix, implies that the linear correlation between any two of them is zero (with respect to the scenarios in the scenario database).

Since the EOFs are linearly uncorrelated, they can be used in an ordinary linear regression analysis without any collinearity issues. This is the approach that we are testing at the moment, although other regression algorithms such as regression tree analyses may also be tested.

The key choice in this method is what variables to include in the analysis, i.e., which variables are used to define the EOFs. The only strict requirement is that the selected variables must be present in both the assessed scenario and in the scenario database (otherwise they are not useful as regressor variables), and no included variable should be perfectly correlated with any other, or the correlation matrix will be degenerate. The variables should also have a significant amount of correlation with temperature or other climate variables in the scenario database, or they are not likely to be useful as regressors.

The computational cost of diagonalizing the correlation matrix may also limit the number of variables that can be included. And as in any regression analysis, if the number of variables is not modest compared to the number of scenarios (i.e., the number of "observations"), it may result in unstable results that are dominated by spurious correlations and have poorer predictive performance than using a more appropriately sized set of variables.

In the initial analysis, we only use emission variables as regressors. In further analyses, it may be interesting to attempt regression based on underlying drivers such as primary energy use per fossil fuel instead, since these variables may reveal other correlations than just the emissions data.

An advantage of this method is that it allows for very flexible modelling of the temperature using any set of variables that are present in both the assessed scenario and the database and that has at least some explanatory power. Using linear regression also allows one to use an extensive existing machinery for assessing sampling uncertainties and explanatory power. A main drawback is that can be computationally expensive if one includes a large set of variables, and selecting a good set of regressor variables may require a good deal of manual exploratory work and trial and error. This method is therefore not necessarily a good choice if the main objective is to simplify the climate assessment relative to the conventional pipeline, but is more suited for contexts where exploring methodological alternatives is of interest.

3.3.5 Outer-bounds infilling: Maximum ranges given modelled emissions and years

Unlike the other methods, this method does not eliminate the climate-modelling step. Instead, it removes the infilling step and seeks to replace it with a simple extremal sensitivity analysis of the effects of the missing emission species.

A common alternative to the elaborate infilling procedure in the IPCC AR6 WGIII pipeline has been to simply assume a default trajectory for each emission species and use these for the emissions that are missing from any given model in a study. This has the advantage of not imposing any external correlations on the assessed scenario but does add an externally imposed time-variable forcing that will cause warming to change by some amount irrespective of what happens in the scenario itself.

In some cases, it can be of interest to know what happens if nothing changes other than the changes imposed by the assessed scenario itself. In this case, one can simply let the missing emissions stay at a historical level from

some starting year onwards. This isn't quite a worst-case sensitivity analysis, since constant emissions may be better than what one would expect in a baseline scenario. But at least for a mitigation scenario, it can still provide a useful limit, since such scenarios often assume that emissions of most species will go down at some point.

Similarly, it can be useful to have an absolute "best-case" limit for how little warming may take place given the modelled emissions in the assessed scenario. In this case, one could for example set the emissions of all non-modelled species to zero from the start year forward. This will of course be an unrealistic assumption, and not useful as an estimate of actual future warming levels. But it can nevertheless be useful as a communication tool.

If the assessed scenario does not run to 2100 and needs to infill years as well as species, one can similarly acreate a sensitivity interval by assuming either that the modelled emissions either continue at the same level as in the final modelled year, or that they go to zero immediately or very quickly afterwards. Again, this is not useful as a projection of actual future temperatures but can still be useful as a communication tool to estimate extreme upper and lower bounds for the temperature in 2100 that are at least somewhat consistent with modelled emissions through 2050 or other final year.

3.4 Updates on simple climate modelling in DIAMOND

In the IPCC Sixth Assessment, climate response uncertainty for mitigation scenarios was represented by parametric ensembles from three reduced-complexity models (RCMs; also known as simple climate models, or SCMs): CICERO-SCM, FaIR, and MAGICC, implemented within the common OpenSCM framework. This process provided consistency across the report, connecting the physical climate assessment in Working Group I to the scenario assessment in Working Group III. In the period since AR6, DIAMOND/CICERO has contributed to two parallel efforts that will underpin the updated climate assessment pipeline for IPCC AR7: (i) a community-wide intercomparison and coordinated constraining of RCMs through RCMIP Phase 3, and (ii) substantial development of our own model, CICERO-SCM, to improve its representation of key Earth system processes.

RCMIP Phase 3. The Reduced Complexity Model Intercomparison Project (RCMIP) provides the coordinated framework through which RCMs are evaluated, calibrated, and applied in climate assessments. DIAMOND/CICERO has co-designed the experimental protocol for Phase 3 (RCMIP3; Romero-Prieto et al., 2025, in review), which is timed to inform the AR7 cycle. The RCMIP3 protocol represents a significant evolution from earlier phases in two respects. First, it introduces a common set of calibration benchmarks drawn from the latest observational products (Indicators of Global Climate Change, Global Carbon Budget), against which all participating models are encouraged to constrain their ensembles prior to submission. This coordinated constraining strategy addresses a key limitation of past intercomparisons, where model-specific calibration choices made it difficult to separate structural from parametric differences in projections. Second, the experimental design places explicit emphasis on carbon cycle evaluation, including new idealised experiments (pulse responses, bell-shaped emission profiles, and the flat10MIP constant-emission experiments co-designed by Sanderson et al., 2025) that cleanly diagnose the transient climate response to cumulative CO_2 emissions (TCRE), the zero emissions commitment (ZEC), and the system's response to net-negative emissions. The protocol comprises 97 experiments in total, spanning both idealised configurations and comprehensive historical and future projections under CMIP6 SSP and CMIP7 Scen7 scenarios, with emissions-driven variants enabling direct comparison with Earth System Model output. CICERO is currently preparing CICERO-SCM submissions for the Tier 1 experiments.

CICERO-SCM development. In parallel with the RCMIP3 contribution, the CICERO-SCM itself has undergone substantial development since the version described by Sandstad et al. (2024). The model now supports a structural switch mechanism allowing users to select between alternative thermal models (the original upwelling-diffusion ocean, or a simplified two-layer model) and alternative carbon cycle representations (the original Joos

impulse-response formulation, or an explicit box model with separate vegetation, soil, mixed-ocean, and deep-ocean pools). For the default carbon cycle, a critical advance has been the introduction of temperature feedbacks on ocean solubility, mixed-layer depth, and land primary production; in earlier releases, the carbon cycle was effectively insensitive to climate due to a coupling bug that has now been corrected. These developments allow the model to report separated land and ocean carbon fluxes, airborne fraction, and other diagnostics requested by the RCMIP3 data protocol, enabling direct evaluation against Global Carbon Budget constraints. The aerosol forcing scheme has also been reformulated to compute forcing per change in annual emissions rather than against a fixed reference year and now supports regional disaggregation. A new pattern-mediated aerosol feedback parameter (delta_lambda_aero) allows the equilibrium climate feedback to vary with the time-evolving aerosol forcing fraction, providing a first-order representation of the forcing efficacy differences that are a major source of uncertainty in historical energy budget constraints. On the infrastructure side, a new parallelisation submodule supports large ensemble generation with Latin Hypercube sampling and chunked memory management, while the calibration workflow has been separated into a dedicated repository (cscm-calibrate) to maintain a clean boundary between model code and tuning choices.

Taken together, these two activities position CICERO-SCM as a more capable and more transparently evaluated tool for the AR7 scenario assessment pipeline. A key objective for the remainder of the DIAMOND project is to combine the RCMIP3-constrained ensemble with the harmonisation and infilling uncertainties discussed in Sections 3.1 and 3.2, delivering an integrated uncertainty assessment in which scenarios providing fewer emission species are associated with correspondingly larger climate response uncertainties.

4 Development of a common baseline scenario

4.1 Rationale and overarching approach

Quantitative modelling has played a central role in assessing NDC ambition and feasibility (van de Ven et al., 2023), enabling the translation of heterogeneous policy targets into consistent estimates of emissions trajectories, energy-system transformations, and long-term climate outcomes. Earlier analyses have shown that successive NDC updates, together with long-term targets (LTTs), have progressively narrowed the gap between current trajectories and Paris Agreement temperature objectives (van de Ven et al., 2023), despite persistent credibility gaps between announced commitments and actual implementation (Rogelj et al., 2023). Multi-model assessments have proven particularly valuable in this context (Tagomori et al., 2026), allowing exploration of structural uncertainties across modelling frameworks while providing more robust insights into the implications of these commitments (Sognnaes et al., 2021).

Here, we have created a common baseline scenario among the six IAM teams, with the collaboration of WP3, that can be used as a starting point for the model scenario intercomparison work that will be pursued under each task of WP5. The purpose of this baseline scenario is to reflect the latest mitigation efforts based on official submitted targets and beyond those already assessed in the literature (e.g., van de Ven et al., 2023; Tagomori et al., 2026). On top of this baseline scenario, thematic shocks, policies and scenario adaptations can be implemented in the different tasks of WP5 to answer the research questions arising from stakeholder engagement.

The first major part of this baseline is based on the Nationally Determined Contributions (NDCs), established under the Paris Agreement, which constitute the core mechanism through which Parties communicate their climate mitigation ambitions, adaptation priorities, and long-term development strategies. Successive rounds of NDC submissions have progressively elevated the importance of transparency, comparability, and credibility in climate governance, as countries transition from broad pledges toward more implementation-oriented targets. Extending target horizons beyond 2030, the latest round of submissions (NDCs 3.0) arrives at a critical moment, following the first Global Stocktake and amid increasing scrutiny over the implementation of current commitments. A striking feature of the current cycle is the marked decline in NDC submissions relative to the second round, with NDC 3.0 submissions representing roughly half of those in the previous cycle (Figure 6). While this does not necessarily reflect backtracking in or withdrawal of commitments, it signals weakening political momentum amid geopolitical instability, energy security pressures, and a growing debate over transition costs.

The second part focuses on Long-term low-emission development strategies (LT-LEDS) featuring targets with longer-term ambition, which many countries have stated to fulfil towards mitigating climate change. These strategies were also submitted under the UNFCCC framework. These come on top of pledged NDC targets, to create another increased level of proposed ambition.

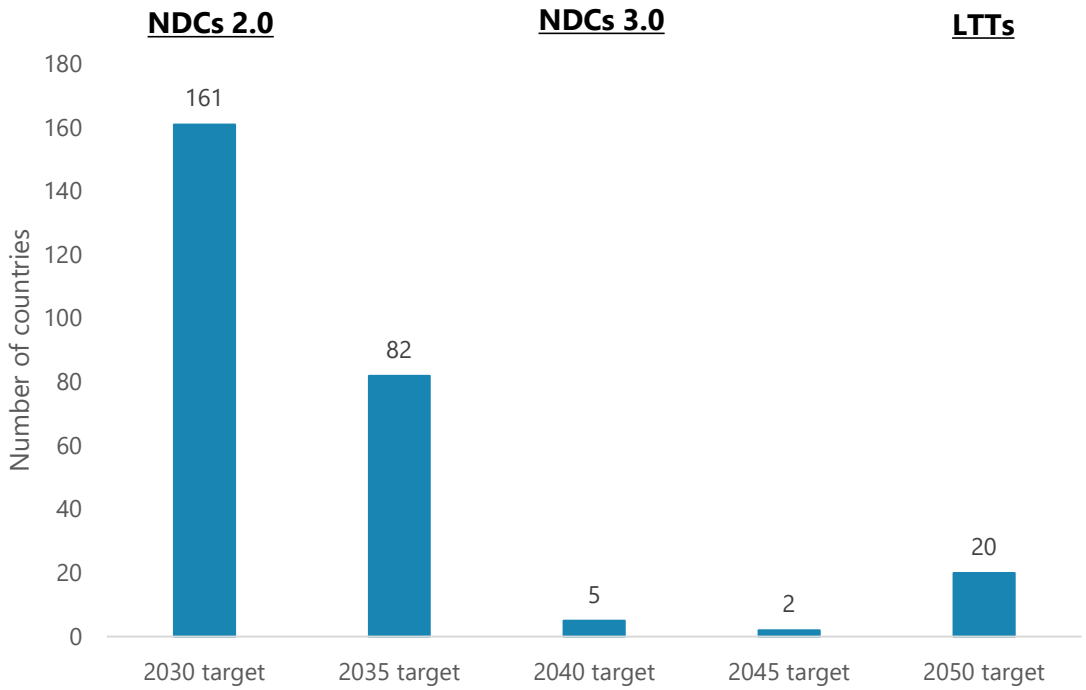


Figure 6. Comparison between the 2nd and 3rd round of NDC submissions.

Considering that many DIAMOND models feature a fine granularity in the EU, the revised National Energy and Climate Plans (NECPs) were explicitly considered, to further operationalise the bloc's NDC commitments by translating overarching climate objectives into sectoral policy pathways across the energy, industry, transport, and land-use sectors. Introduced in 2019 and later updated to reflect the EU's more ambitious climate goals, draft revisions of the NECPs were published in 2023. By May 2025, 24 final NECPs had been submitted and are considered in this scenario (Figure 7 & 8).

The core approach towards developing this baseline scenario is based on modelling emissions targets that follow the three aforementioned types of targets: i) the Nationally Determined Contributions (NDCs) and their latest updates as of and after COP30 for non-EU regions; ii) the updated (2025) National Energy and Climate Plans (NECPs) for EU member states (depending on the aggregation of each model; and iii) Long-term targets (LTT) for both EU (member state level) and non-EU regions. Considering these national commitments in the baseline scenario enables us to conduct policy-relevant scenario assessments using models with enhanced representation of climate impacts, the circular economy, finance, labour, and human behaviour. In the next section we describe the baseline protocol in detail, including aspects related to harmonisation of parameters, assumptions on extensions beyond the last mitigation targets, aggregations of regions, handling of missing emission types.

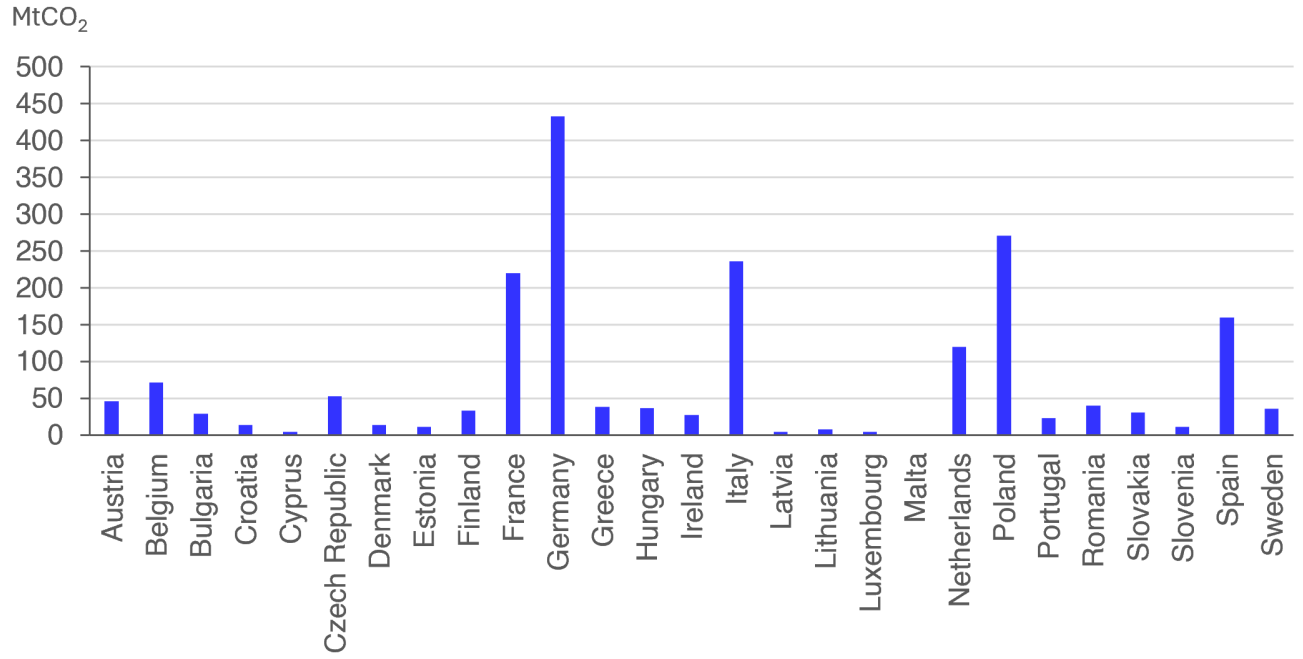


Figure 7. NECP emission target for European member states without LULUCF

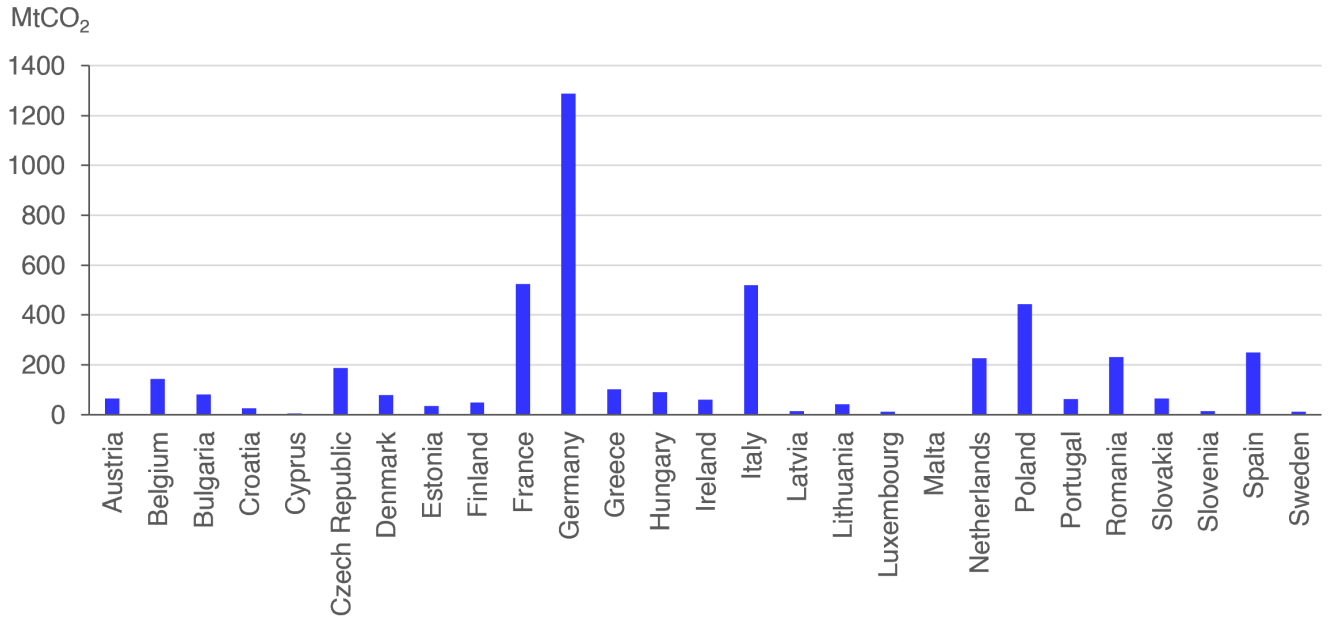


Figure 8. NECP emission target for European member states with LULUCF

4.2 Protocol for the common baseline scenario

A harmonised modelling protocol was developed to ensure consistency across the six participating frameworks while preserving model-specific structures and regional detail. The protocol is based on the systematic implementation of updated Nationally Determined Contributions (NDCs), including revised National Energy and Climate Plans (NECPs) in EU Member States, and long-term targets (LTTs), through quantified emissions pathways for both EU and non-EU regions.

For non-EU regions, country-level targets from the latest NDC submissions and LTTs were translated into absolute

emissions trajectories and aggregated to model regions using a harmonised methodology that accounts for differences in target years and conditionality. Countries lacking explicit commitments were represented through reference-scenario assumptions to ensure full regional coverage. Sri Lanka's NDC target is not considered, as it is the only country with a cumulative emissions target.

For EU Member States, updated NECP targets for 2030 and derived emissions pathways toward 2035–2050 were implemented at national or model-aggregation level. Intermediate-year targets were estimated through linear interpolation.

In cases where an aggregated model region includes both countries with established targets and countries without targets, an adapted approach based on the CD-LINKS protocol was applied to calculate regional targets. For 2030, most countries include either an unconditional or conditional target that can be directly used for aggregation. Some countries define reduction targets (relative to BAU) in their NDCs but do not provide sufficiently quantified baselines to estimate absolute emission levels. For these cases, reference or benchmark values for 2030 were estimated by assuming that emission intensity (i.e., emissions per unit of GDP) between 2019 and 2030 remains constant.

Historical 2019 emissions from EDGAR and projected changes in GDP between 2019 and 2030 from the SSP2 database were used to derive the necessary targets. However, some countries are missing from the NDC dataset due to a lack of targets or missing projections of GDP and population in the SSP database. In most cases, these are small island countries with negligible shares of global emissions. Nonetheless, for Venezuela, Cuba, Bolivia, Libya, and Bahrain, which have more significant emission shares, population change from 2019 to 2030 was used together with 2019 emissions to estimate 2030 reference emissions, assuming constant emissions per capita over time. These estimates are used as implicit targets for these countries within aggregated regions to ensure full representation.

For countries with a different target year than 2030, you can linearly interpolate to 2030 using the following formula:

$$E_{i,Y^*}^{\text{tar}} = E_{i,2019}^{\text{histo}} + \frac{Y^* - 2019}{Y_i - 2019}\left(E_{i,Y_i}^{\text{tar}} - E_{i,2019}^{\text{histo}}\right)$$

Where:

- $E_{i,2019}^{\text{histo}}$ = historical emissions of country i in 2019.
- E_{i,Y_i}^{tar} = country's i **absolute** target emissions in its declared year Y_i

Beyond 2030, to define the target for an aggregated region sum of the absolute targets of all countries within the region that have targets, and the (no policy) reference-scenario emissions of countries that do not have targets, assuming that their share within the aggregate group (from the model) remains the same as in 2030 based on the NDC+Ref data is considered.

In case of an aggregated region in the model contains countries with different target years, the target year used by the majority of countries (for most cases this should be 2035) was selected. For countries whose target year differs from that majority year, then linear interpolation was applied between that country's target and its 2030 emissions.

The following approach reflects this process:

- T =set of countries **with** targets.
- N =set of countries **without** targets.

- Y^* =chosen common target year (the majority-year you select, e.g. 2035).
- Y_i = country's i declared target year.
- $E_{i,2030}^{\text{NDC or ref}}$ = emissions of country i in 2030 (either unconditional/conditional targets for countries with)—or reference values for countries without target).
- E_{i,Y_i}^{tar} = country's i **absolute** target emissions in its declared year Y_i .
- $E_{agg,2030}^{\text{NDC+Ref}}$ = emissions of aggregated region in 2030, based on the sum of unconditional/conditional targets for countries with targets and reference values for countries without targets.
- E_{agg,Y^*}^{ref} = model reference emissions for year Y^* for the aggregate region (*model-based*).

We then bring every country to the common year Y^*.

For $i \in T$ (country has a target), the target expressed in year Y^* is:

$$E_{i,Y^*}^{\text{tar}} = \begin{cases} E_{i,Y_i}^{\text{tar}}, & \text{if } Y_i = Y^*, \\ E_{i,2030}^{\text{NDC or ref}} + \dfrac{Y^* - 2030}{Y_i - 2030}\left(E_{i,Y_i}^{\text{tar}} - E_{i,2030}^{\text{NDC or ref}}\right), & \text{if } Y_i \neq Y^*. \end{cases}$$

For $j \in N$ (country has no target), use the modelled reference emissions in the common year of the aggregate region, assuming that the share of country j in year Y^* remains the same as in the 2030 NDC+Ref data:

$$E_{j,Y^*}^{\text{no_tar}} = \frac{E_{j,2030}^{\text{ref}}}{E_{agg,2030}^{\text{NDC+Ref}}} * E_{agg,Y^*}^{\text{ref}}.$$

The final aggregated regional absolute target for year Y^* is:

$$E_{Y^*}^{\text{agg region}} = \sum_{i \in T} E_{i,Y^*}^{\text{tar}} + \sum_{j \in N} E_{j,Y^*}^{\text{no_tar}}$$

The shares of countries not represented in 2030 can also be ignored in subsequent steps.

Mitigation effort after net zero is reached

A constant mitigation effort was assumed beyond the year in which each region reached net zero. The carbon price extension method was used, whereby the equivalent carbon price in the net-zero year was extrapolated using the per capita GDP growth rate of the different regions up to the end year of each model. The equivalent carbon price represented the value of carbon that would have yielded the same emissions reduction as the NDC/NECP+LTT policies in a region (if 0, a carbon price of 1 was used instead).

$$CP_{region\ j}^{yr\ i\ post-NZ} = CP_{region\ j}^{yr\ of\ NZ} * \frac{\frac{GDP_{region\ j}^{yr\ i\ post-NZ}}{Population_{region\ j}^{yr\ i\ post-NZ}}}{\frac{GDP_{region\ j}^{yr\ of\ NZ}}{Population_{region\ j}^{yr\ of\ NZ}}}$$

Calibration of targets to the level represented by the models

Some models include only CO_2 emissions or lacked representation of LULUCF emissions. In such cases, the targets included in this protocol were calibrated under the assumption that the share of emissions observed in real

historical data in the model base year remained constant throughout all modelling periods.

Parameter harmonisation

Harmonisation will follow, to the extent possible, the soft harmonisation guidelines introduced in D3.2 (section 4).

Minimum assumptions that should be followed include:

- For non-EU regions, use **SSP2** for GDP and population.
- For EU regions, **2024 EU Ageing Report**
- Update GDP projections up to 2029 based on **IMF**.

4.3 Emissions and energy-system implications of updated commitments

Acknowledging that many of our models are still under development, here we offer some preliminary insights from the first implementation of the baseline scenario in the DIAMOND models. The final implementation of the baseline which will be used in the remaining task under WP5, will be featured in the final consolidation of WP5 in D5.7. Notably, we assessed the emissions and energy-system implications of updated NDC and NECP commitments using our six-model ensemble (comprising GEMINI-E3-EU, OMNIA, OPEN-PROM, NEMESIS-World, GCAM-Europe, and CLEWs-EU), implementing this harmonised modelling protocol to ensure cross model consistency while preserving framework-specific structures and regional detail.

Table 2. Model ensemble

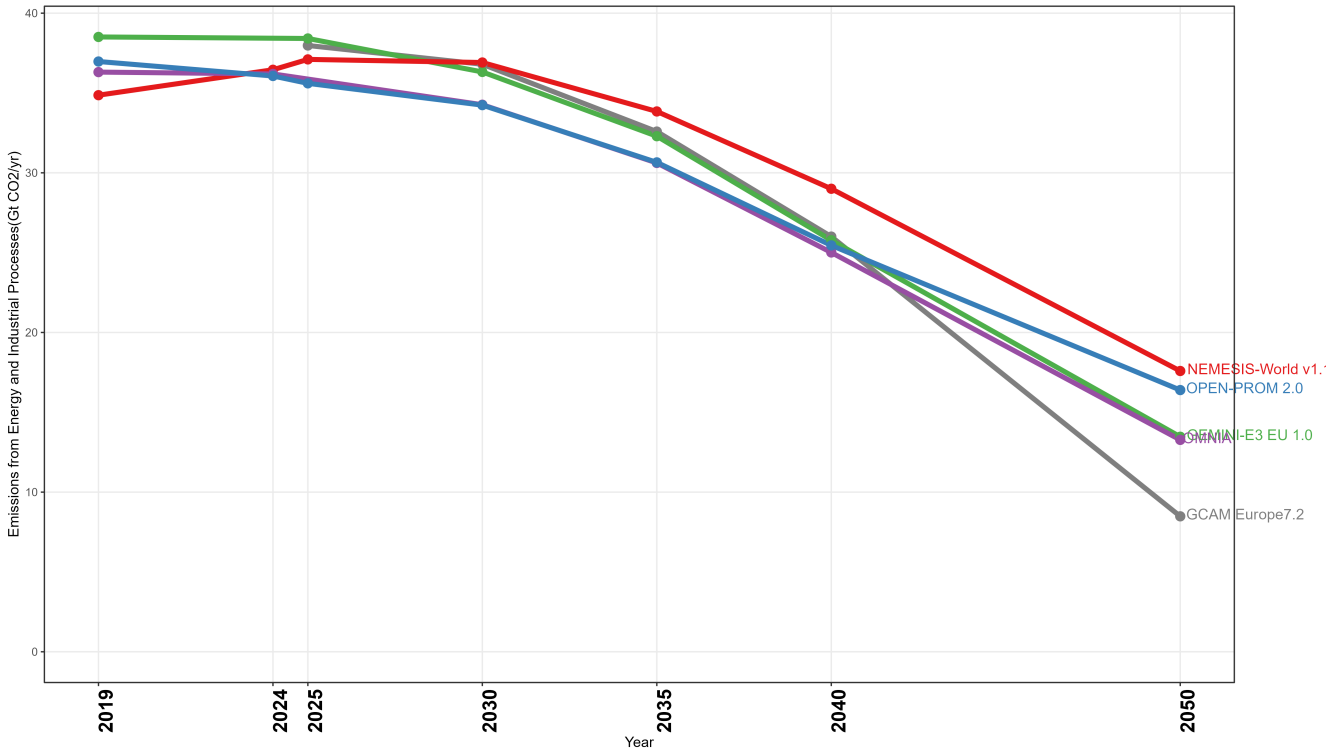
Characteristic	CLEW-EU	GCAM-Europe	OMNIA	OPEN-PROM	GEMINI-E3 EU	NEMESIS-World
Solution Horizon	Intertemporal optimisation (perfect foresight)	Recursive-dynamic	Intertemporal optimisation (perfect foresight)	Recursive-dynamic	Recursive-dynamic	Recursive-dynamic
Typology	Optimization	Simulation	Optimization	Optimization	Macro-econometric	Computable General Equilibrium
Spatial resolution	27	66	28	39	24	22
Temporal Horizon	2050	2050	2050	2100	2050	2050
Energy technology diffusion	Modelling of supply energy based on cost optimization	Modelling considering choice function (cost plus penalty cost due to inconvenience)	Modelling of supply energy based on cost optimization	Modelling of supply energy based on cost optimization	Modeling of energy consumption through nested CES representation	Embodied CES production functions (firms and households) and logistic functions in power generation sector

Technological change	Exogenous (Technological substitution is endogenous (e.g. from ICE vehicles to electric vehicles). Technological improvement (e.g., lower CAPEX, higher efficiency within same technology) is exogenous)	Exogenous	Exogenous	Exogenous	Exogenous	Exogenous
Behavioural change (yes/ no)	No (yes, only when soft-linked with the behavioural module)	Exogenous	No (yes, only when soft-linked with the behavioural module)	Exogenous	Yes Endogenous (driven by price and income)	Yes Endogenous (driven by price and income)
CCS Technologies included	- Biomass, natural gas and coal with CCS (for electricity generation) - Coal and natural gas with CCS (in industry) - SMR with CCS (for hydrogen production) - Direct Air Capture	- Biomass, natural gas and coal with CCS (for electricity generation) - Coal and natural gas with CCS (in industry) - SMR with CCS (for hydrogen production) - Direct Air Capture	- Biomass, natural gas and coal with CCS (for electricity generation) - Coal and natural gas with CCS (in industry) - SMR with CCS (for hydrogen production) - Direct Air Capture	- Biomass, natural gas and coal with CCS (for electricity generation) - Coal and natural gas with CCS (in industry) - SMR with CCS (for hydrogen production) - Direct Air Capture	Coal with CCS, Gas with CCS, oil with CCS and Biomass with CCS	Yes, from 2035 (Coal with CCS, Gas with CCS and Solid biomass with CCS)

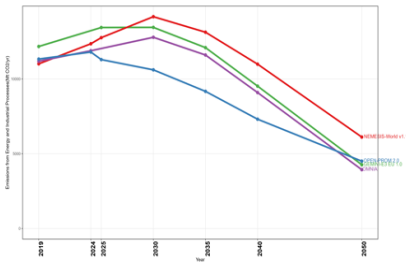
4.3.1 Emissions

Although we constraint the models on the emissions trajectories, here we discuss how the models implemented said targets and reflect on the implications of the targets as quantified by the models. The paths show declining energy and industrial process emissions under the updated NDC and NECP pathways across all models, although the pace of reductions remains moderate compared with pathways aligned with the most ambitious goals of the Paris Agreement. In the updated NDC_LTT scenario, global energy and industrial process emissions decline to 34–36 $GtCO_2$ in 2030, 30–33 $GtCO_2$ in 2035, and 13–17 $GtCO_2$ in 2050. The results further highlight that emissions in the EU and Japan decline more rapidly than in the United States, while emissions from major emitters such as China and India peak around 2030 before declining thereafter. OMNIA and NEMESIS-World project a substantial long-term decline in emissions, indicating a strong transition toward decarbonisation in Brazil over the coming decades to reach the net zero target in 2050. The emission in Brazil is expected to gradually reduce from 500 Mt CO_2 in 2019 to 2035, while afterwards emissions decrease more sharply to reach net zero in 2050. In NEMESIS-

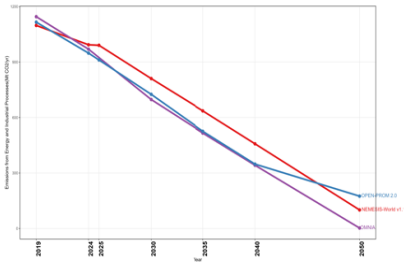
World, emissions in Brazil fall more rapidly compared to OMNIA and reach net negative by 2050.



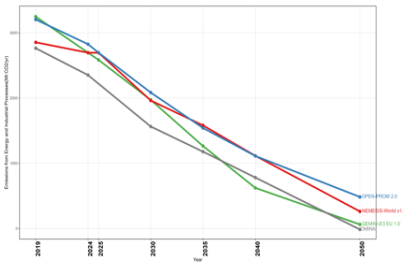
World



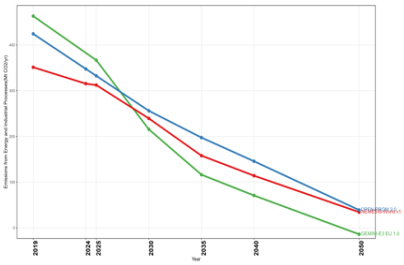
China



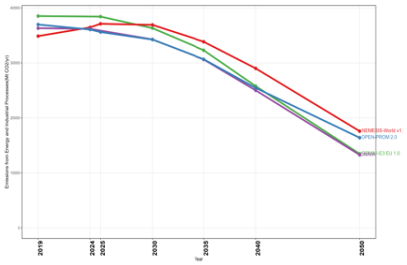
Japan



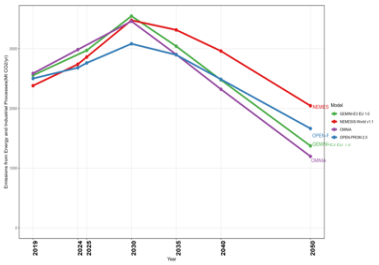
EU



UK



USA



India

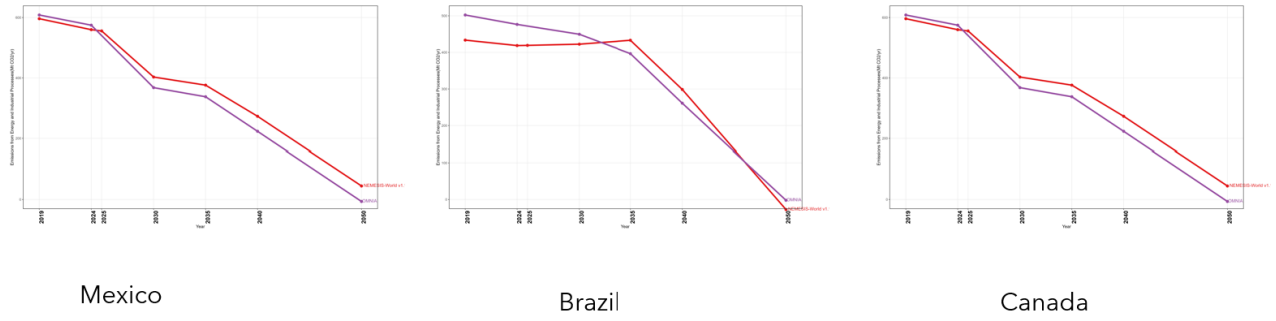


Figure 9. Emissions Pathways from different models

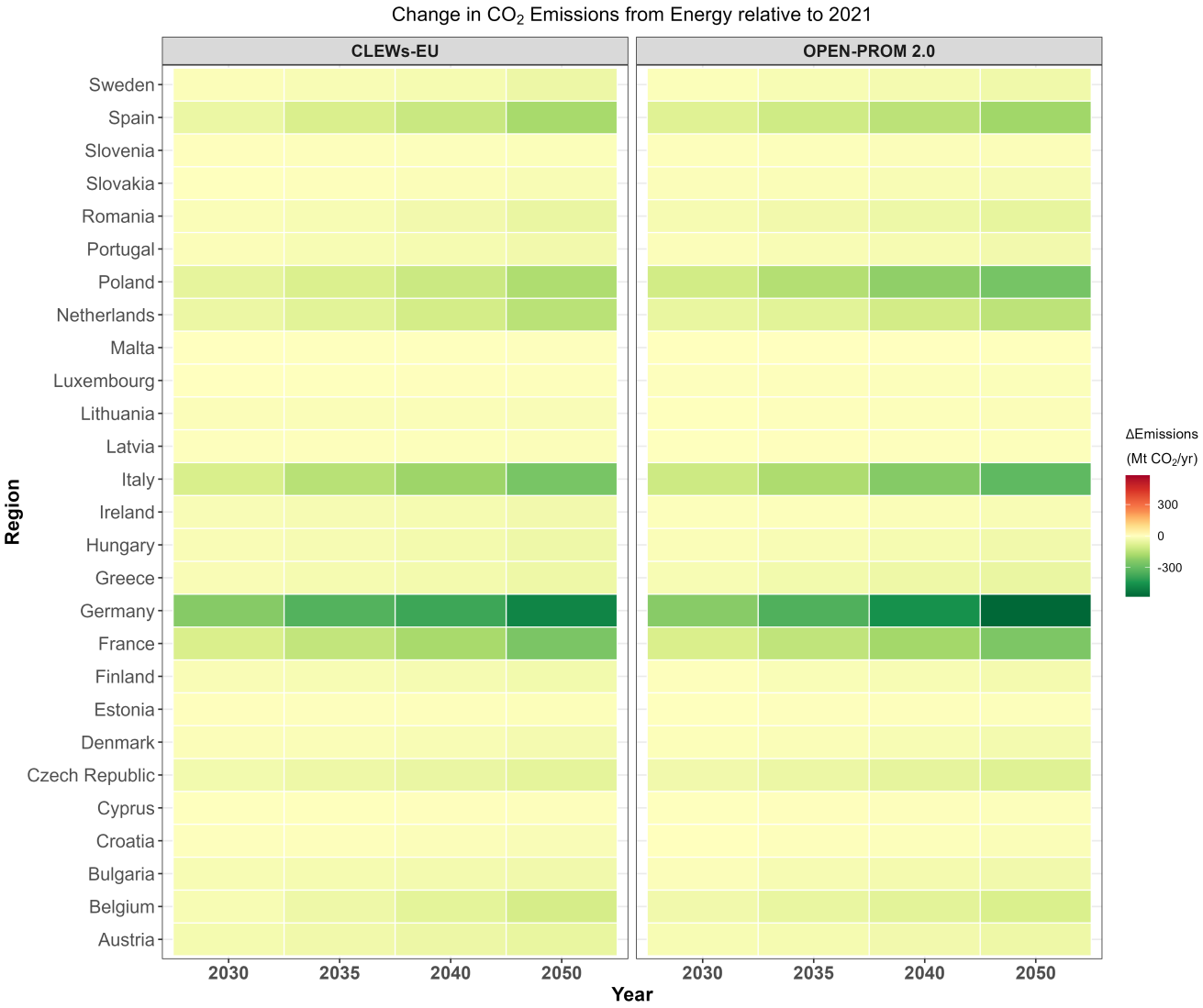


Figure 10. Change in the energy related emissions in European member states

Figure 10 shows the changes in CO_2 emissions from the energy sector across 27 EU member states for 2030, 2035, 2040, and 2050 relative to the 2021 across two models that have modelled EU member states individually. The largest declines expectedly occur in the high emitting nations such as Germany, Poland, Italy and France where reductions deepen through to 2050. Minor changes in the absolute emissions occur in the smaller member states such as Malta, Luxembourg and Cyprus, which start with low base year emissions. Both the models show similar spatial and temporal patterns but for some countries OPEN-PROM shows larger reductions in the later decade

compared to CLEWs-EU. This reflects the impact of different modelling approaches (see Table 2) with the perfect foresight optimisation CLEWs-EU model starting decarbonisation earlier than the recursive dynamic OPEN-PROM, even under similar emissions constraints.

4.3.2 Temperature

Following the temperature assessment pipeline presented in Section 3, Table 3 shows the projected temperature rise for the baseline scenario across four different models for the years 2050 and 2100. Table 3 shows low, median, and high estimates of future temperature change across four models, illustrating the range of uncertainty in the projections. For 2050, the models show relatively similar results, with median temperature increases ranging from 1.77°C to 1.91°C and most high estimates remaining below 1.9°C, except for GEMINI-E3 EU projecting up to 2.15°C. By 2100, the projected warming becomes more pronounced and uncertain, with median values ranging from 1.79°C to 1.94°C which is still higher than 1.5°C target and high estimates increasing to as much as 2.26°C. This implies that governments need to strengthen their targets to reach the most ambitious climate target, as well as to make effort to account for this inherent uncertainty. We note that the temperature assessment pipeline was not run for GCAM-Europe as the emissions pathway will be finalised with the release of the next version of the model (v8). However, based on the tentative results presented here, the internal temperature assessment of GCAM-Europe based on Hector indicates a peak temperature increase of 1.75°C before 2100, within the range and close to the lower end of the median estimation indicated in Table 3. CLEWs-EU is a strictly European model, lacking the necessary global implication for a temperature assessment to be meaningful.

Table 3. Temperature in 2050 and 2100

Temperature in 2100			
	Low	Median	High
OPEN-PROM	1.82	1.85	1.87
NEMESIS-World	1.74	1.94	2.26
OMNIA	1.6	1.79	2.1
GEMINI-E3 EU	1.77	1.91	2.15
Temperature in 2050			
OPEN-PROM	1.82	1.82	1.83
NEMESIS-World	1.74	1.81	1.86
OMNIA	1.70	1.77	1.83
GEMINI-E3 EU	1.77	1.91	2.15

4.3.3 Electricity Generation Mix

Figure 11 compares the secondary energy electricity generation mix in the baseline scenario—for the years 2019, 2035, and 2050. The results show a substantial increase in electricity generation over time across all models,

particularly by 2050, with renewable energy sources becoming increasingly dominant. Wind and solar energy contribute the largest share of growth in most models, reflecting a transition toward cleaner energy systems. Among the models, OMNIA shows the largest increase in total electricity generation by 2050, driven primarily by a very large expansion in wind and solar power. OPEN-PROM indicates a balanced increase across intermittent (wind, solar) and non-intermitted sources (nuclear and hydro). In NEMESIS-World the shift towards renewables occurs more gradually, reflecting greater inertia in the model as a result of its macroeconometric nature. The decline in coal and oil remain in the short term and gas continues to play a transitional role in the model. GCAM-Europe also points to a gradual transition towards renewables, with total electricity generation in 2050 being comparable to GEMINI-E3 EU. These results show an overall need to transit towards low carbon electricity technologies despite difference in the scale and pace of transition of different sources across models in order to reach the national commitments mentioned in NDC and LTTs.

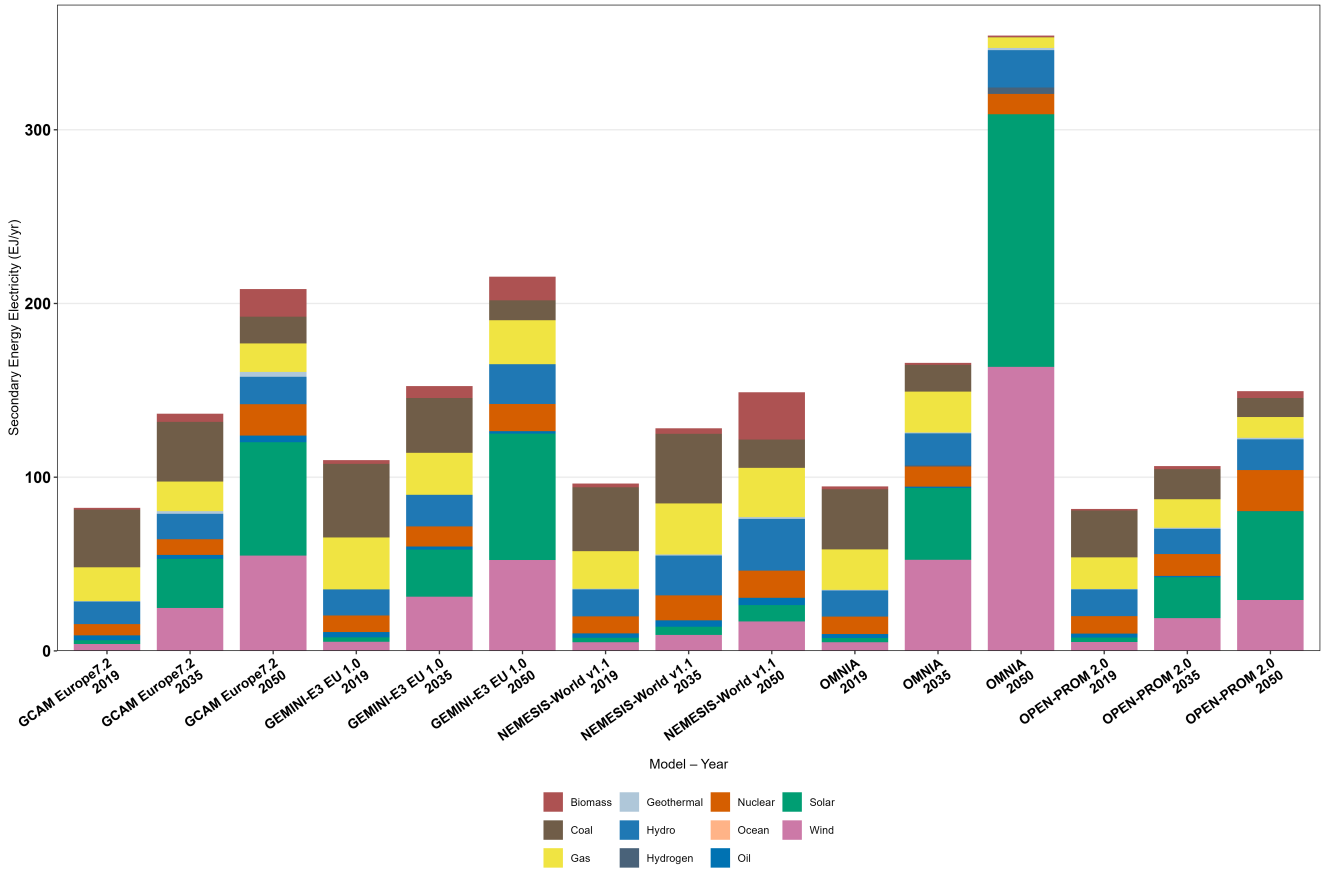


Figure 11. Electricity generation mix in 2019, 2035, and 2050

4.3.4 Primary Energy mix

Figure 12 compares the global primary energy mix for the years 2019, 2035 and 2050. The results highlight a significant change in the primary energy mix over time, with all models projecting gradual transition away from fossil fuels towards low carbon sources. Oil and gas remain major contributors to global primary energy in all scenarios but renewables sources such as wind, solar, biomass and hydro increase significantly across most models. The share of oil is still dominant in 2050 in the NEMESIS-World model compared to the other models. At the same time the share of biomass also increases substantially in 2050 in the primary energy mix compared to other models in 2050. Similar to NEMESIS-World, the share of biomass in GCAM-Europe increases in 2050

compared to 2019, along with increases in solar and wind energy, reflecting a shift away from coal. In GEMINI-E3 EU and OPEN-PROM model, we see a gradual decline in the total primary energy demand in 2050 from 2019. In GEMINI-E3 EU, efficiency improvement and endogenous feedback effect to prices results in the decline in the primary energy compared to models like OMNIA and NEMESIS-World where there is a gradual increase in the total primary energy in 2050 compared to 2019.

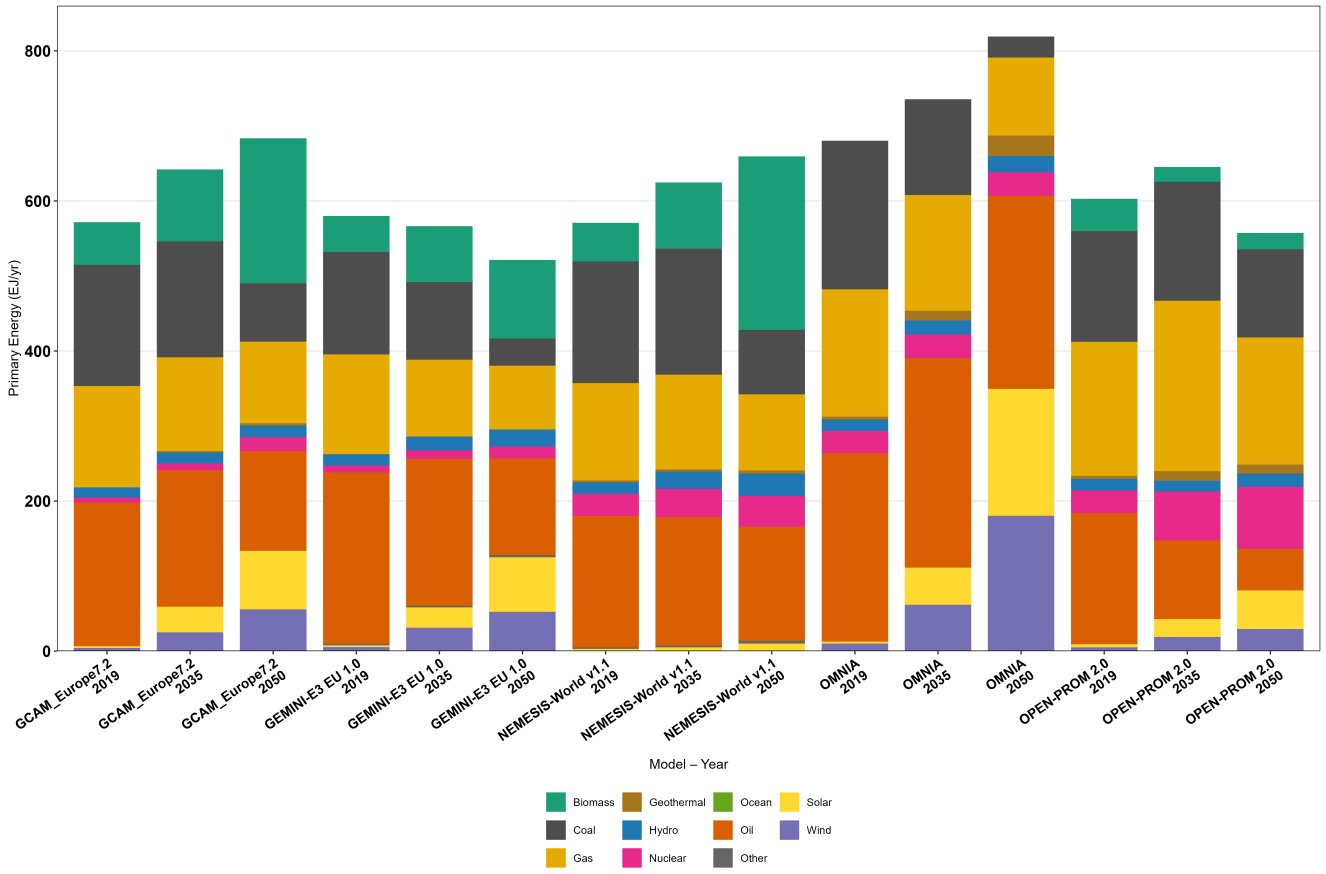


Figure 12. Primary Energy mix in 2019, 2035, and 2050

4.3.5 Reflections on the current implementation of the baseline scenario

This exercise has been instrumental for the next stages of using the models to respond to specific research questions under the various tasks of WP5. The protocol dictates targets with higher interdependence (i.e., changes in one country may have implications for other regions) compared to the stylized shocks implemented so far during model development, and as such, it constitutes a stronger stress test. Still, many of the behaviours identified could accurately be traced back to the underlying economic and choice theory of each model. This indicates that as the final versions of the models are progressively rolled out, the DIAMOND IAMs are on good track to be able to evaluate mitigation scenarios aligned with country's net zero target, serving as a basis for the detailed scenarios presented in the next section.

5 DIAMOND Scenario Narratives

This section presents the DIAMOND Scenario Narratives developed from the co-creation process, through which research questions and scenario dimensions have been shaped in close interaction with stakeholders. Across the section, the narratives reflect a diverse set of themes, including climate impacts and adaptation, system resilience under disruptive shocks, circular economy transitions, financial system dynamics, labour market adjustments, behavioural heterogeneity, and interactions with the broader sustainable development agenda.

The section is structured around the different tasks under Work Package 5, each addressing specific stakeholder-informed research questions through targeted scenario exercises.

Task 5.2 examines climate impacts and adaptation, focusing on how increasing wildfire frequency and intensity affect land use, carbon storage, and mitigation strategies in the EU. By additionally linking a fire model with IAMs, the analysis captures feedback between climate change and land-based mitigation.

Task 5.3 investigates the effects of disruptive events, such as heatwaves and trade shocks, on the resilience of the European power sector and broader energy transition pathways.

Task 5.4 explores user-driven scenarios that extend IAM capabilities, including circular economy policies for heavy industry, financial system dynamics, labour market transitions, and behavioural factors influencing technology adoption. These scenarios highlight distributional effects, system constraints, and policy trade-offs.

Task 5.5 integrates climate mitigation analysis with the Sustainable Development Goals (SDGs), assessing synergies and conflicts across environmental, social, and economic dimensions.

5.1 Task 5.2: Climate impacts and adaptation

A significant part of the activities of this task will be performing a post-analysis of NDC and NECP impacts derived from the baseline scenario. For this process, we will employ the METEOR model to produce regional impacts on heating and cooling degree days, and an emulator to estimate the impacts on crop yields.

Hence, here we focus on our additional work on estimating the impact of fires, which will require the development of further scenarios on top of the baseline. This focus is based on a dedicated research question received during our stakeholder engagement process.

5.1.1 RQ1: The impact of fire carbon emissions on land use pathways in the EU

The frequency and intensity of wildfires have increased significantly due to climate change in the last decade. Around 20% of burnable land area is now experiencing fire weather conditions that have moved beyond historical variability, driven by rising temperatures and increasing atmospheric dryness, which in turn create drier fuels, more extreme fire conditions, and longer fire seasons. At the same time, the frequency of major wildfire events causing 10 or more fatalities has increased more than threefold between 1980 and 2023, highlighting the growing severity of impacts (Cunningham et al., 2025). Beyond immediate damage, forest fires reduce the global land carbon sink and can even trigger long-term biome shifts, which may take decades or longer to reverse due to system inertia (Burton et al., 2024). Fire is not only a consequence of climate change but also a feedback mechanism that can further accelerate it. This has important implications for national climate targets, particularly where land-based mitigation is central, and raises complex trade-offs in land use between carbon storage, bioenergy production, and food security. It is important to include this feedback in the IAM model to understand these trade-offs.

5.1.1.1 Research question

The scenarios being developed under Task 5.2 will answer research questions that have been posed by stakeholders engaged in earlier phases of DIAMOND.

RQ: How does climate change influence the frequency and intensity of forest fires? How does this affect land carbon stores and land use strategies?

The research question explores future fire projections at the EU level provided by a global fire model (IAM-FIRE) while the second part of the question explores the implications of these future impacts on climate policy packages based on land systems strategies such as afforestation/reforestation (A/R). The research questions will be investigated through: 1) a novel modelling chain linking IAM-FIRE to two IAMs; and 2) a scenario design looking at EU level climate policies with and without fire impacts and fire response mechanisms. The two components are described below.

5.1.1.2 Modelling framework

The modelling framework is composed of three main models and tools:

IAM-FIRE: The IAM-FIRE framework is used to project fire impacts, such as Burned Area (BA) and Carbon Emissions (CE) using IAM inputs (initially from GCAM v8.2; to be generalised here). The projections are computed for two scenarios following SSP-RCP combinations. The statistical engine of IAM-FIRE will be trained on the European region to better account for the specific roles of each driver to predict burned areas. This will improve the predictions compared to the original global ones. Projections will be run using a factorial decomposition approach allowing to fix some drivers while others are allowed to vary. To capture the climate impact signal, the projections will allow dynamic climate and vegetation factors while keeping land use and socio-economic assumptions fixed at base year value. The goal is to isolate the effects of climate change from other drivers of fire regimes.

GCAM-Europe: GCAM-Europe is an expansion of the well-established Global Change Analysis Model (GCAM) that can serve as a powerful tool for in-depth analysis of European climate policy. GCAM-Europe explicitly represents land use, agriculture, water resources, and energy extraction at the subregional level. Operating within a global framework, the model enables integrated assessment of policy impacts both across and within European regions, while also capturing spillover effects in other regions in the world.

CLEWs-EU: The CLEWs-EU model is developed within the OSeMOSYS (Open-Source Energy Systems Model) modelling framework which is a long-term cost-optimisation energy system model. The CLEWs-EU model builds on the structure of the Global CLEWs model with several enhancements being implemented, such as the improved linkages between the energy and land with water modules.

The models and tools are combined to model EU-level scenarios accounting for the impacts of fire on different variables relevant for the land system role in climate mitigation (Figure 13). The outputs of IAM-FIRE are implemented through two different feedback mechanisms in GCAM-Europe and in CLEW-EUs:

Emission factors in GCAM-Europe: The feedback in GCAM-Europe focuses on CO_2 emissions from forest fires. Depending on future climate pressure, forests will be sequestering less carbon due to increasing fire intensity. These exogenous emissions will decrease the mitigation potential of fire-prone forests compared to other forests in mitigation pathways. The model will re-allocate where forest expansion ideally occurs within Europe due to this feedback.

Burned areas in CLEWs-EU: The feedback in CLEWs-EU focuses on BA attributed to forest fires. Areas with high BA will have increased pressure from land competition due to the loss of productive land from fire. This can lead to adjustment in the allocation of land throughout the continent, depending on the climate policy and global

Funded by
the European Union

radiative forcing assumptions.

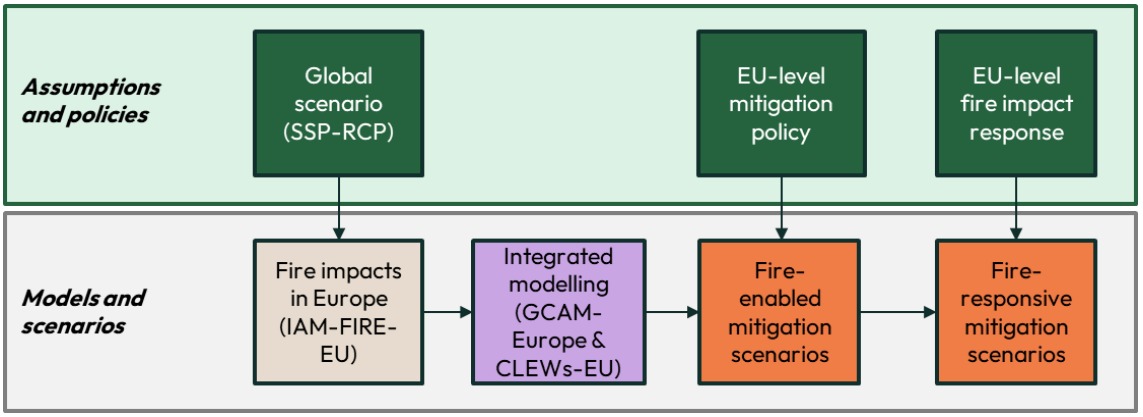


Figure 13. Modelling framework for the study of fire impacts on land system mitigation using the modelling framework IAM-FIRE and the integrated assessment models GCAM-Europe and CLEWs.

5.1.1.3 Scenario design

The scenario design will represent these two feedback mechanisms for different sets of global socio-economic assumptions and policy packages at the EU level (Table 1). Specifically, the following climate policies and response mechanisms will be modelled:

European policy: EU-wide targets in line with Fit-For-55 are applied for renewables (42.5% of final energy) and energy efficiency (11.7% reduction in final energy w.r.t. 2020) to achieve -55% emission reduction in 2030, along with a continuation of policies and a CO_2 target moving towards net-zero in 2050 (aligned with the DIAMOND baseline—see Section 4).

Fire response: In GCAM-Europe, anticipation of future fire risks in forests at the basin level will be implemented to allow the model to adjust the demand of mitigation capacities in high-risk basins. This will contrast with the scenario with impacts but no responses which will respond myopically to the integration of fire impacts at each time period.

Table 4. Scenario design to assess the role of fire impacts on the European Union climate policy package Fit-for-55

Global assumption (SSP-RCPs)	European policy	Fire impact (Yes/No)	Fire response (Yes/No)
SSP1-2.6	No climate policy	No	No
SSP1-2.6	EU-wide policy	No	No
SSP1-2.6	EU-wide policy	Yes	No
SSP1-2.6	EU-wide policy	Yes	Yes
SSP2-4.5	No climate policy	No	No
SSP2-4.5	EU-wide policy	No	No
SSP2-4.5	EU-wide policy	Yes	No

SSP2-4.5	EU-wide policy	Yes	Yes
SSP3-6.6	No climate policy	No	No
SSP3-6.6	EU-wide policy	No	No
SSP3-6.6	EU-wide policy	Yes	No
SSP3-6.6	EU-wide policy	Yes	Yes
SSP5-7.6	No climate policy	No	No
SSP5-7.6	EU-wide policy	No	No
SSP5-7.6	EU-wide policy	Yes	No
SSP5-7.6	EU-wide policy	Yes	Yes

5.1.1.4 Expected results

The integration of fire impacts in the models will enable the quantification of their impact on the European climate policies. In particular, the results will analyse the following outcome variables/processes of interest:

The drivers of the fire and its impacts in Europe will be derived from the results of the IAM-FIRE statistical model, restricted to Europe and to trajectories of fire impacts under different global assumptions following the SSP-RCP framework. To address the second part of the research questions, the extent of the reallocation of productive land and changes in the area dedicated to CDR (in particular A/R) in Europe will be assessed.

Carbon price and other cost related indicators will be used to assess the economic implications of achieving a specific mitigation target when climate impacts are explicitly considered.

The impact on other economic activities, such as trade flows, will also be assessed by exploring shifts in the imports and exports of commodities resulting from the loss or degradation of production in Europe along with shift in the mitigation strategies in other sectors by exploring the changes in energy supply and emissions from other sectors, caused by the diminished capacity of land to sequester carbon.

5.2 Task 5.3: A bumpy road to net-zero: systematic assessment of disruptive events

The European Union's power sector faces compound risks from climate change and geopolitical instability that may undermine the feasibility of planned decarbonisation pathways. Heatwaves reduce the output of thermal, hydro, and renewable generation assets, increase cooling demand, and raise the cost of capital for energy investments. Trade disruptions, whether from geopolitical tensions or supply chain failures, increase the cost of imported energy. These disruptions interact: a heatwave that suppresses domestic generation at the same time as import costs are elevated creates a compounding stress that linear, single-shock analyses cannot capture. Standard integrated assessment model (IAM) scenarios typically assume smooth transitions and do not systematically test what happens when multiple shocks coincide under varying levels of system resilience. This task addresses that gap.

5.2.1.1 Research Questions

This exercise is guided by two applied research questions:

RQ1: In the presence of trade disruption, how do heatwaves affect the robustness of the EU power sector under various resilience assumptions?

RQ2: What are the cascading impacts of these disruptions in the power sector on electrification in the EU's end-use sectors?

5.2.1.2 Modelling Framework

The study employs the Disruptive Events-Resilient Pathways (DERP) framework (Al Khourdajie et al., under resubmission), which provides a systematic structure for introducing disruptions into mitigation scenarios and comparing outcomes across resilience configurations. Three capacity expansion IAMs are used: GCAM-Europe (BC3), OMNIA (E4SMA), and OPEN-PROM (ICCS). Their outputs, formatted in the Integrated Assessment Modelling Consortium (IAMC) data template, serve as input to openTEPES (COMILLAS), an electricity dispatch model that performs high-resolution operational simulations to stress-test system configurations under the same compound shocks.

The analysis, spatially disaggregated at the EU level (NUTS0 where possible) with a global backdrop, covers the power and end-use sectors, and extends to 2050. Disruption parameters are applied only to EU member states for the period 2035 to 2045. The dispatch analysis focuses on a 2040 snapshot.

5.2.1.3 Scenario Protocol

The disrupted scenarios build on the NDC-LTT scenario, i.e., the project's baseline mitigation pathway with economy-wide carbon taxes. Two disrupted variants are constructed, distinguished by their resilience configuration:

- Low techno-economic resilience: an upper bound on capacity additions is imposed at the NDC-LTT level, preventing the model from compensating for the disruption through accelerated deployment.
- High techno-economic resilience: no such constraint is applied, allowing the system to respond freely to the shock.

In both variants, carbon prices are fixed at NDC-LTT levels following the introduction of the disruption, so that emissions increase and mitigation ambition is effectively reduced.

The compound disruption consists of two elements. The heatwave shock operates through three channels: (i) reduced capacity factors for thermal, hydro, and renewable technologies, calibrated from CMIP6 projections under SSP5-8.5 and country-level climate stressors; (ii) increased cooling degree days, calibrated from GCAM-EU baseline projections; and (iii) increased cost of capital (20% for energy supply technologies, 10% for the rest of the economy). The trade shock is a sustained increase in the cost of imported gas and electricity from outside the EU, applied at 25% and 50% levels.

Combining these disruption and resilience dimensions with sensitivity variants yields a total of 13 scenarios.

5.2.1.4 Dispatch Analysis

Using IAM outputs as input, openTEPES performs hourly operational simulations for 2040 under two dispatch configurations: (i) domestic-priority dispatch, simulated via high cross-border costs, and (ii) renewable-priority dispatch, simulated via penalties on curtailment and hydro spillage. The output includes wholesale electricity price

profiles, cross-border trade flows, curtailment levels, and reliability metrics such as non-served energy. These outputs will inform complementary off-model analysis.

5.2.1.5 Key Output Variables

The IAMs report electricity capacity by technology (biomass, coal, gas, oil, solar, wind, geothermal, hydro, nuclear), final energy by sector and vector, CO_2 emissions from energy and industrial processes and from electricity supply, and operational costs per MWh per technology. The latter is specifically required for the IAM-to-openTEPES handover.

5.3 Task 5.4: Stretching the frontiers – user-driven scenarios building on expanded modelling framework

Task 5.4 spans several topics, on circular economy, finance, labour market, behavioural driven shift in final demand and technology deployment. Each of these topics are considered as separate sections.

5.3.1 The role of circular economy policies in decarbonising steel, cement and aluminium sectors

This modelling scenario task is an inter-model comparison exercise assessing circular economy (CE) policies to decarbonise three key energy-intensive industrial sectors (steel, aluminium and cement). It builds on the modelling capability developed under DIAMOND, described in Deliverable 4.1, which focuses on the representation of circular economy (CE) measures in three IAM models – ENGAGE-OMNIA, OPEN-PROM and GCAM Europe. The aim of this model intercomparison is specifically to assess the effects of CE policies at global and regional level using these three IAM models.

5.3.1.1 Research questions

Scenarios are being developed that respond to the following research questions (RQs), shaped through engagement with a range of stakeholders, under WP2:

- RQ1: What is the contribution of CE policy packages in delivering regional and global climate goals?
- RQ2: What are the broader impacts of these CE policies across different regions and sectors?

The first question explores how implementation of CE policy package helps deliver climate policy targets, and the balance with other mitigation options. Implementation will span across Europe and in other regions of the world.

The second question further explores the distributional implications spatially and across sectors, resulting from the implementation of policy packages in different geographies.

There are a number of scenario dimensions that will be used to assess these RQs, focused on: i) climate policy ambition, ii) circular economy ambition, and iii) regional implementation.

5.3.1.2 Scenario design

Climate policy ambition

There are two levels of global climate policy ambition that we will consider, derived from the Baseline Scenario Protocol.

- NDC only

- NDC and Long-term targets (LTTs)

Circular economy policy package and ambition

Two policy packages will be developed, representing medium and strong level of circular economy policy interventions. These policy packages extend across all three industrial sectors of focus. A provisional list of CE policies was explored with determination as to whether the policies could be directly applied in all models, or only indirectly (based on proxies or inputs from ENGAGE).

Table 5. Proposed CE policies for consideration in scenarios

Sector	Policy Measure	Description	Include?	
			Direct	Indirect
Steel, Aluminium	Taxes to primary production	Applying taxes on conventional steelmaking (e.g., blast furnace–basic oxygen route), conventional aluminium smelting (from alumina)	Yes	
Steel, Aluminium	Subsidies to secondary production	Providing financial support to production from scrap (EAF route)	No	Yes
Steel, Aluminium and Cement	Carbon tax/ ETS	Introducing a tax on carbon emissions from industry sector production.	Yes	
Steel	Subsidies to hydrogen-based Scrap based-EAF production	Supporting low-carbon steelmaking using scrap based electric arc furnaces.	Yes	
Steel, Aluminium, Cement	CBAM	Tax on goods entering the EU based on their embedded carbon to incentivise secondary production.	No	Yes
Cement	Taxes on clinker production	Levy a tax on clinker output to discourage high-clinker cement and incentivise substitution.	No	Yes
Cement	Subsidies for low-clinker cement	Provide financial support to producers adopting clinker substitutes	Yes	
Cement	Mandatory standards on clinker ratio	Legally require maximum clinker-to-cement ratios in cement formulations (e.g., <65%).	Yes	

The **medium ambition** CE policy package introduces incremental measures focused on improving recycling and resource efficiency. In the steel sector, this means moderate scrap recycling targets, limited incentives for EAF adoption and basic sorting improvements. For aluminium, it includes moderate scrap recycling targets and limited support for secondary aluminium. In cement, it encourages clinker substitution and efficiency improvements along the supply chain.

The **high ambition** CE policy package applies stronger measures across all sectors and integrates them with climate policies, aligning with mechanisms like CBAM and EU ETS. For steel, this includes mandatory high quality scrap standards, strict targets on EAF production, taxes on primary production, and mandatory secondary input content. For aluminium, it sets strict targets on secondary input content and imposes taxes on primary production. In cement, it mandates clinker substitution ratios, incentivise carbon capture, and enforces circular design standards.

Regional implementation of policy packages

The final scenario dimension is the region where the policy package will be introduced. The reason for differentiating regional implementation is to understand the implications of EU policy alone, both for EU decarbonisation and for the rest of the world. This is then contrasted with a more global implementation of policies in different regions, backed by the relevant international industry trade bodies.

Table 6. Regional implementation of CE policy packages.

	Scenario	Description
1	NoCE	There are no specific CE policies implemented

2	MedCE_EU	Europe leads medium ambition of CE policies
3	HighCE_EU	Europe leads high ambition of CE policies
4	MedCE_GBL*	Europe alongside international partners leads medium ambition of CE policies
5	HighCE_GBL*	Europe alongside international partners leads high ambition of CE policies

*Note: International partners include OECD countries and the major BRICS economies of China, India, Russia, Indonesia, South Africa, and Brazil. These scenarios will only be modelled in ENGAGE-OMNIA and OPEN-PROM

The above scenarios will then be run with both levels of climate policy ambition (described in section 5.3.1.2), resulting in a **total of ten scenarios**.

Additional scenario considerations

There are a number of other assumptions required for harmonisation of scenario implementation across the models including -

- Socioeconomic drivers: these will be taken from the Baseline Scenario Protocol (see Section 4.1)
- Baseline production (demand) for three industrial commodities – steel, aluminium and cement.

5.3.1.3 Modelling approach

To enable improved representation of CE policies, the OMNIA-ENGAGE models are linked. This is because IAMs such as OMNIA typically exclude detailed representations of critical flows of material along supply chains, as well as across the entire lifecycle of goods and services. This leads to overlooking the potential effects that some circular economy actions, such as reuse and recycling of materials, may have on the economy, on the demand of specific commodities (e.g. secondary metals) and ultimately on decarbonisation strategies.

This linkage will harness the strengths of both models. While OMNIA provides a detailed representation of industrial technologies and their energy consumption (which a global economic model such as ENGAGE does not model in detail), it lacks the representation of material flows needed for assessing circular economy policies. In particular, it does not capture the flow of materials through domestic and international supply chains—as the ENGAGE model does—from ore mining to scrap recycling, and how this translates into demand for energy services, a key input to OMNIA. Unlike ENGAGE, OMNIA does not represent trade in materials, goods and services, which are crucial to evaluate the impact of decarbonisation and circular economy policies across regions and sectors.

In the OMNIA-ENGAGE soft linking approach, energy system configurations and emission reduction pathways will be passed from OMNIA to ENGAGE, leveraging OMNIA's detailed technological representation of energy system transformation and the uptake of industrial technologies. Based on this specific energy system configuration, ENGAGE determines an economy-wide equilibrium by adjusting upstream and downstream markets. Subsequently, the adjusted demand for goods and services, e.g. metals and construction materials, and changes in GDP will be fed from ENGAGE to OMNIA to update the demand requirements for such products in OMNIA and resulting energy demand. The linkage process is shown in Figure 14 below.

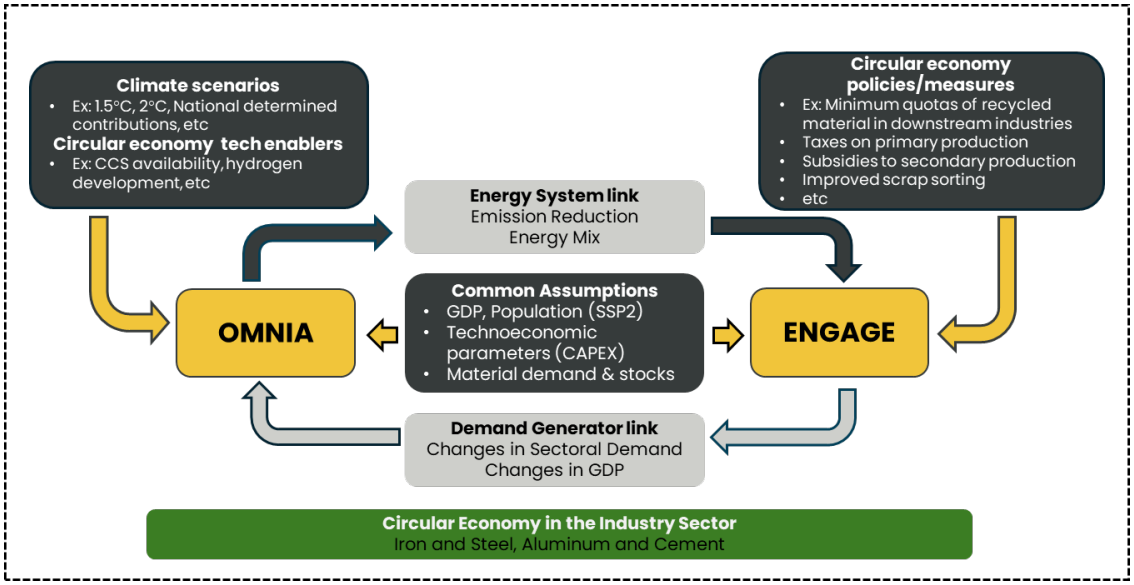


Figure 14. Conceptual linkage and information flow between ENGAGE and OMNIA

The other participating models, GCAM-Europe and OPEN-PROM will not have such a linkage but will benefit from characterisation of CE policy developed in initial OMNIA-ENGAGE modelling, for use in the intercomparison exercise.

5.3.2 Policy Scenarios for Finance in IAMs

The work conducted in the DIAMOND project to extend the representation of finance in IAMs lends itself to the exploration of several relevant policy scenarios. The module allows for the disaggregation of Weighted Average Costs of Capital (WACC) by country and technology type, which can be employed as a discount factor in cost-minimising investment decisions within the energy sector. The WACCs can also be set to vary over time, either according to a financial learning curve applied to the rate as a whole, or through changing shares of underlying debt and equity instruments used in the financing mix by technologies as they mature. Particularly the latter approach allows for the exploration of policy solutions relevant to national and Central Bank decision makers.

5.3.2.1 Research Questions

In the project, we have developed and implemented (in CLEWs-EU and NEMESIS-World) a financial market module that endogenises and quantifies the financial market dynamics implied by exogenously imposed transition scenarios. This module allows us to address our key research questions:

- How do we model and calibrate the investment demand dynamics by technology and risk-return profile?
- How do we model and calibrate the intermediation of savings to investment through financial instruments?
- How do real economy bottlenecks, risks and constraints, affect risk-return profiles across asset classes?

5.3.2.2 Scenario and model design

Green Preferential Interest Rates

This policy scenario relates to the cost of financing available to investing firms. It would put a ceiling on interest rates charged on loan debt by Private Banks for renewable energy projects. This can be interpreted as, for example, changes in micro- and macro-prudential regulation that incentivise Private Banks to issue green loans due to

favourable reserve requirements (Dikau & Volz, 2018), adjusted weights for green projects in credit risk assessment, and public guarantees for green projects in the absence of collateral (as in Lamperti, Bosetti, Roventini, Tavoni, and Treibich (2021)). All of these measures would allow Private Banks to reduce interest rates on green loans, by mitigating information asymmetry and improving profitability. As a result, the cost of debt for energy technologies would fall, and the share of debt in the financing mix would rise, therefore decreasing the WACCs.

One option would be to calibrate from the lowest empirical WACC values across the EU from the time period of 2030, for example according to the dataset of (Hatton, Staffell, Jansen, Oluleye, & Hawkes, 2025):

Technology	Minimum Viable WACC
Biomass	5
Geothermal	7
Hydro	4.5
Solar PV	5
Wind Onshore	4.5
Wind Offshore	5.5

This would particularly benefit renewable technologies in EU countries with unfavourable financing conditions, including recently ascended member states.

Another option, for IAMs such as NEMESIS-World that include endogenous country-specific policy rates, is a *thermostatic strategy*. This means that preferential green interest rates are triggered by macroeconomic conditions, such as phasing in lower rates during periods of con-tractionary monetary policy meant to counterbalance an inflationary shock scenario. When macroeconomic conditions are favourable, commercially competitive technologies such as onshore wind do not receive additional support.

Green Policies for State Investment Banks

This policy scenario relates to the quantity of financing available to investing firms, by increasing the volume of funding through State Investment Banks. This is particularly relevant to financially immature technologies, which in early life-cycle stages rely more heavily on public grants, since they are evaluated as highly risky by Private Banks, and have issues accessing bond and equity markets . This policy scenario directly increases the quantity of financing through State Investment Banks (which was around 15% of cumulative finance according to calculations by (Mazzucato & Semieniuk, 2018), thereby ameliorating credit constraints; it also works through decreasing the WACC, which will be determined by a larger share of the lower cost of debt.

State Investment and Development Banks play a crucial role in directly providing credit, but also financially de-risking innovative sectors, creating sustainability standards for financial instruments, and signaling to potential co-investors on large projects. As early movers, they aid immature technologies to become commercially competitive for Private Bank credit and equity markets.

Through providing larger volumes of funding at early stages of the technological life cycle, the dynamics of financial learning and financial maturation in the module imply the possibility of a virtuous cycle of technology development, which was not possible in the standard representation of finance in IAMs. This can help evaluate the relative benefits and cost-effectiveness on increased State Investment Bank mandates in the EU, as prior modeling efforts with simple energy sectors showed positive results from this policy approach (e.g(D'Orazio & Valente, 2019)

Green Policies for Quantitative Easing

This policy scenario increases the quantity of financing available to investing firms, by increasing the volume of

funding through the bond market. This is particularly relevant to more mature technologies such as solar PV and wind (onshore and offshore), which can use bonds for long-term investments. While this policy scenario directly increases the quantity of financing through bonds, through central bank asset purchases the bond price can increase and the interest rate fall; this also works through decreasing the WACC, which will be determined by a larger share of the lower cost of debt.

Improvements to green taxonomies and expansion of carbon-neutral bond volumes has been a feature of the European Green Deal, including the introduction of the European Green Bond Standard (EuGBs) in 2024. In DSGE models that explored the use of unconventional monetary policy (e.g., (Diluiso, Annicchiarico, Kalkuhl, & Minx, 2021{Ferrari, 2023 #3091; Ferrari & Nispi Landi, 2023) the use of market-neutral and green Quantitative Easing are also associated with increased financial stability and business cycle smoothing. However, unlike IAMs, these models have a low level of detail for energy sectors, industries, and emissions.

Through providing larger volumes of funding at later stages of the technological life cycle, emphasis is put on scalable green technologies in IAM decarbonisation trajectories and the mobilisation of private finance, which was not possible with the standard representation of finance in IAMs. The ongoing discussion for central banks about the relevance of explicit decarbonisation goals to their price and financial stability mandates(van Tilburg & Simić, 2021) would also benefit from simulation results on potential emission reductions from such policies. Thus, evaluating the impacts of larger bond volumes and green asset purchases within IAMs is highly relevant for central bank decision making.

5.3.3 Policy Experiments for Labour Market Extensions

5.3.3.1 Research Questions

In the project we have developed and implemented (in GEMINI-E3 EU) a module that endogenises and quantifies the labour market dynamics implied by exogenously imposed transition scenarios. This module allows us to address our key research questions:

- How can we model and calibrate skill supply dynamics by demographics and region?
- How can we model and calibrate labour demand dynamics by sector, technology and region?
- How can we assess the impact of policy that will promote the transition through facilitating faster and smoother labour reallocation?

5.3.3.2 Scenario and model design

The directed search labour module is well-suited to investigate the impact of policies that address labour shortages during the zero-carbon transition by e.g., affecting worker reallocation across sectors. The structure of our module explicitly captures search frictions, wage formation, and matching processes, allowing for a more realistic representation of labour market adjustment dynamics than standard modelling approaches. In particular, the framework generates endogenous unemployment, sector-specific labor market tightness, and transition delays, all of which are central to assessing the costs and distributional implications of labor reallocation across sectors, i.e. structural change.

A key feature of the module is that workers face heterogeneous search costs when moving across sectors. These costs can vary by origin and destination sector as well as by worker type (e.g., skill level), allowing the model to capture barriers to mobility that are observed empirically. This structure also enables the simulation of policies aimed at reducing these frictions, such as targetted training and reskilling programs. These policies can be implemented in the model as reductions in cross-sector search costs, which increase the relative attractiveness of

expanding sectors (e.g. green industries) and accelerate the reallocation of labor away from declining (i.e. brown) sectors. In addition to facilitating mobility, these policies reduce structural unemployment by improving the alignment between worker skills and job requirements.

A second important feature of the module is the role of information in shaping job search behaviour. Workers do not perfectly observe all available job opportunities and may therefore fail to target sectors with higher job-finding probabilities or wages. This is captured through a dispersion parameter governing the sensitivity of worker choices to differences in expected outcomes. Policies that improve information—such as job-matching platforms, public employment services, or information campaigns—can be represented as increasing this sensitivity. As a result, workers will direct their search more efficiently, leading to improved matching outcomes and a reduction in labour misallocation across sectors.

The model also captures the role of labour demand through vacancy creation decisions by firms. Firms post vacancies subject to costs, and these costs can vary across sectors. This allows for the analysis of policies that directly stimulate labour demand, such as hiring subsidies or tax incentives for job creation in targeted sectors. In the model, such policies reduce vacancy posting costs, leading to higher vacancy creation, increased labour market tightness, and higher job-finding rates for workers. This channel is particularly important for accelerating the absorption of workers displaced from declining sectors.

Finally, the framework incorporates wage determination through bargaining between workers and firms, where the worker's outside option (i.e., unemployment benefits received if they don't work) plays a central role. This allows for the evaluation of policies related to unemployment benefits and income support. Increasing the value of the outside option improves income security for unemployed workers and raises equilibrium wages, but may also reduce incentives for job search and vacancy creation. Conversely, lower benefits strengthen search incentives but may come at the cost of reduced welfare for workers. The model therefore provides a natural setting to analyse the trade-off between equity and efficiency in the design of social security and income support policies during the transition.

These policy channels exhibit important complementarities. For example, reducing search costs through training programs may not be sufficient to generate rapid reallocation if workers lack information about opportunities in expanding sectors. Similarly, hiring subsidies may have limited effects if workers face high mobility barriers. Combining policies that target different frictions, such as training, information provision, and hiring incentives, can therefore lead to significantly larger impacts than any single policy in isolation.

For integration into computable general equilibrium or integrated assessment frameworks, the effects of these policies are calibrated in reduced form through changes in labour mobility parameters, i.e., the elasticity of transformation in CET functions. Policies that reduce search costs, improve information, or enhance matching efficiency can all be interpreted as increasing effective labour mobility. This mapping, however, would abstract from the underlying mechanisms captured by the directed search framework, in particular the dynamics of unemployment, vacancy creation, and wage formation. Our structural module provides additional insights into transition dynamics and welfare effects that are not captured in the standard aggregate representations.

Overall, the directed search labour module enables a richer analysis of labour market policies in the context of structural transitions. By explicitly modelling the frictions that govern worker reallocation, it allows for the evaluation of both the efficiency and the distributional consequences of alternative policy designs targetting labour markets, as well as the interactions between different policy instruments.

Funded by
the European Union

5.3.4 Policy Experiments for Final Demand

5.3.4.1 Research Questions

In the project we have developed and implemented (in GCAM-Europe and OPEN-PROM) a module that endogenises and quantifies the adoption of heat pumps to illustrate the interaction between information networks and budget constraints in exogenously imposed transition scenarios. This module allows us to address our key research questions:

- How can integrated assessment models (IAMs) better account for household heterogeneity in forecasting green technology adoption?
- And how can this enable them to better represent a wider range of policy options?
- How can policies reduce disparities in the adoption of green technologies, stemming from variations in household characteristics?
- What role do psychological factors play in the adoption of green technologies, and how can policies take this into account?

5.3.4.2 Scenario design

The technology substitution module which we employ is well-suited to investigate the impact of policies promoting household adoption of sustainable technologies for final demand. The structure of the module is one which endogenously generates S-shaped diffusion curves, which are characteristic of patterns of innovation diffusion. Because this is rare in the current state of the art for IAMs, our module allows for a more meaningful simulation of the impact of the standard tax and subsidy policies on the diffusion of adoption of sustainable technologies. Additionally, our module has two key features which enable meaningful simulation of policy options which cannot be adequately represented in the baseline IAM.

The first key feature is that the heterogeneity of agents is such that households of different income levels make different technology substitution decisions. This enables model simulations to investigate the impact of policy incentives that vary in magnitude according to household income. For example, the module can apply additional investment subsidies for residential heat pumps to low-income households. Many IAMs model only a single representative agent household, and so cannot implement this kind of policy at all. GCAM-Europe does model households by income decile, and so could apply such a policy. However, because income level does not affect the substitution decision in the baseline model, there would be no difference between the reactions of a low- and a high-income household to additional subsidies.

To implement additional investment subsidies for low-income households in our module, we can simply apply a higher investment subsidy on residential heat pumps to deciles below an income threshold. This reduces the levelised cost of heating associated with the technology for affected households, which makes the investment more attractive. Additionally, it directly reduces the up-front cost that affected households face, which enables adoption by low-income households which would otherwise have been unable to afford that investment cost.

Second, the module includes the influence of information, another key feature of models of innovation diffusion. This allows for the simulation of information-based policy options, such as public information campaigns. Innovation diffusion exhibits local spillovers because individuals are more willing to adopt an innovation if others around them are already adopting it, which both normalizes adoption and increases the likelihood that the individual obtains more detailed information about the benefits of the innovation. These spillovers are local because an individual's perception of the state of the market is biased towards their own local area of the social

Funded by
the European Union

network. Public information campaigns seek to accelerate diffusion by informing everyone about the benefits of the innovation even if their local network does not include many existing adopters.

In our module, a household's locally biased perception of the state of the market affects its technology substitution decisions. For this reason, segments of the market which are less likely to adopt for other reasons have that resistance compounded by the fact that their subjective perception of the state of the market suggests a smaller adoption rate than exists in reality. We can simulate an information campaign policy by adjusting the market perceptions of agents to more closely mirror the actual market state within the country. This increases the adoption rate of households in segments of the market where adoption is lagging.

Importantly, these two policy simulations have a natural complementarity. Households in low-income areas are less likely to adopt high cost sustainable innovations like domestic heat pumps because it is more difficult for them to afford the investment. This fact limits the prevalence of existing adopters in such areas, which further reduces the likelihood of adoption even when the technology becomes subjectively affordable. If additional investment subsidies for residential heat pumps are offered to low-income households, this may cause the technology to become affordable, but the lack of locally available information will make adoption slow. An information-based policy can directly ameliorate the information constraint, increasing the effectiveness of the additional subsidies.

5.3.5 People in Transition

Electrification of end-use sectors is one of the key mitigation strategies, enabling deep decarbonisation when combined with a clean power system to reach climate goals. Electrification of the transport sector through deployment of electric vehicles (EVs) is critical to reducing emissions from transport sector that is one of the largest contributors to GHG emissions. However, the pace, distribution and scale of the EV adoption depend on household level decisions which are shaped by income, access to charging infrastructure, preferences, and other behavioural factors and not only on the cost of EVs. Integrated assessment models (IAMs) often simplify these dynamics, potentially overlooking important variations across socio-economic groups and the implications for both adoption pathways and equity outcomes. Improving the heterogeneity in the models helps capture some of these dynamics.

5.3.5.1 Research Questions

Table 7. Research questions received and addressed for policy scenarios of People in Transition

People in Transition	How can integrated assessment models (IAMs) better account for household heterogeneity in forecasting green technology adoption? And how can this enable them to better represent a wider range	What strategies can enhance resilience to climate change and transition impacts across different households?	What role do psychological factors play in the adoption of green technologies, and how can policies take this into account? M-	How can policies reduce disparities in the adoption of green technologies, stemming from variations in household characteristics?	How are certain sectors impacted differently by shifts in energy demand and production?	How do extreme climate events influence public perception and social acceptance of green mobility and clean energy technologies over time?

	of policy options?					
RQ as taken forward by Uni Basel	1. How does including household heterogeneity in IAMs influence forecasts for electric vehicle adoption (under different external events)?	2. Which policies are effective in stimulating the transition to e-mobility while mitigating negative financial impact on low-income households?	3. How does including household decision making based on psychological factors in IAMs influence forecasts for electric vehicle adoption?	4. Which policies enable households of different socio-economic groups to participate in the transition to e-mobility?	Not addressed in Task 5.4	Not addressed in Task 5.4

RQ1 and RQ3 will be addressed through the soft-links established in T4.6 between the behavioural module and CLEWs-EU, GCAM-Europe, and OMNIA.

RQ2 and RQ4 will be addressed through a dedicated agent-based model (ABM) of EV adoption drawing from the behavioural module developed in T4.6.

5.3.5.2 Scenario Protocols

RQ1 and RQ3: Soft-link with IAMs

Scenario 1: Baseline

Baseline scenario of EV adoption across the EU based on cost optimisation, CO_2 constraints, and technological trends (i.e., IAM runs without soft-link). This scenario serves as the reference point against which behavioural and heterogeneity effects are assessed (see Scenario 2).

Scenario 2: Consumer heterogeneity and psychological factors

Soft-link scenario with constrained EV adoption based on behavioural data, where the soft-link constrains adoption rates based on consumer preferences derived from discrete choice experiments. Expected direction: lower aggregate adoption compared to Scenario 1, due to psychological barriers and preference heterogeneity not captured by cost optimization.

Scenario 3: Consumer heterogeneity and psychological factors, with disruptive events

Scenario 2 extended with supply-side shocks (import tariffs of 20% and 50%) and market volatility shocks (uncertainty in gasoline and electricity prices). Expected direction: reduced EV adoption relative to Scenario 2, with larger effects under the 50% tariff condition.

Outcomes

- Indicator 1: Total EV adoption over time across European countries.
- Indicator 2: Growth in other emission-reducing technologies (e.g., heat pumps, CCS).
- Indicator 3: Cost of technological shift away from EVs.

We compare outcome indicators across scenarios to investigate the effect of including psychological data of

heterogeneous consumer preferences (Scenarios 1 vs. 2) and disruptive events (Scenarios 2 vs. 3) on total EV adoption across countries.

RQ2 and RQ4: ABM on EV adoption

Scenario 1: No-policy baseline

Baseline scenario of adoption of new EVs and pre-owned EVs based on agent preferences and technological trends derived from discrete choice experiments, without financial policy instruments. The ABM includes a model on Germany, the United States, and South Africa.

Scenario 2: Financial policies

Scenario 1 with financial policy instruments: subsidies on new EVs, subsidies on pre-owned EVs, and a carbon tax. Expected direction: increased total adoption relative to Scenario 1, with distributional effects across income groups (e.g., richer households adopt more EVs).

Scenario 3: Financial policies and disruptive events

Scenario 2 extended with supply-side shocks (import tariffs of 20% and 50%), market volatility shocks (uncertainty in gasoline and electricity prices), and a regulatory intervention (ICE sales ban).

Outcomes

- Indicator 1: EV adoption across the agent population, disaggregated by income group.
- Indicator 2: Financial benefits (subsidies received) and burdens (carbon tax paid) of EV-promoting policies across income groups.

We compare outcome indicators across scenarios to investigate the effect of financial policies (Scenarios 1 vs. 2) and disruptive events (Scenarios 2 vs. 3) on total EV adoption and the distribution of EVs and of policy-related financial flows across income groups.

5.4 Task 5.5: Expanding the SDG target space: placing climate action in broader sustainable development

5.4.1 Overarching objectives

The activities under this task aim to draw on the newly developed modelling capacity established throughout the project, encompassing both the individual IAMs (WP3) as well as the dedicated modules (WP4), and crucially their integration into coherent analytical frameworks, to shed light on the complex interplay between climate action and the broader sustainable development agenda.

A natural entry point for this analysis is the Sustainable Development Goals (SDGs), which are typically operationalised through dedicated indicators that can be represented in IAMs, such as the SDG target space featuring a collection of such indicators (van Vuuren et al., 2022). The enhanced modelling capacity developed in DIAMOND provides an opportunity to build on and expand such work (see our SDG Model Coverage Matrix in the IAM PARIS Platform).

5.4.2 Stakeholder insights

Based on the stakeholder integration activities under WP2, the multi-stakeholder discussion groups produced a set of research questions to influence the specific activities designed in this task. These include:

- How is bridging SDGs and decarbonisation in different regions affected by disruptive events and/or

geopolitical shifts, and different political priorities?

- What is the role of technologies (e.g., NETs and other game changing including non-tech innovations) and social acceptance in the interplay between land use, biodiversity preservation, and mitigation, and what are their broader SDG implications?
- Which technologies or transformations (e.g., digital economy) contribute the most towards a sustainable, resilient energy system, in the light of extremes and shocks?
- What is the interplay between SDG13 and SDG15 (i.e., what is the impact of mitigation on biodiversity preservation, and vice versa, of biodiversity preservation on the climate system), and what are broader benefits.
- Which SDG-15-related actions and constraints should be quantified and imposed on IAM scenarios?

Considering the breadth of scientific fields represented in the sustainable development agenda, these research questions are not explicitly meant to formulate exact dedicated exercises to be pursued and directly respond to them. Rather, they constitute a reflection of stakeholder priorities on thematic topics within the sustainable development agenda that could be prioritised, crucially focusing on highlighting such dimensions within the context of broader SDG-wide analysis.

Notably, we can observe a strong preference among stakeholders for topics related to "SDG15: Life on Land", and crucially the interplay between climate change mitigation and biodiversity preservation, as well as the role of specific technologies (e.g., Negative Emissions Technologies) on this dynamic in these two dimensions. At the same time, there is also interest in aspects related to disruptive events and geopolitical tensions, crucially focusing on implications for technologies and regions. Although parts of this insight on disruptive events will inherently be addressed within the dedicated task on disruptions (e.g., Task 5.2), the stakeholder feedback here hinted at providing a broader SDG perspective in this discussion. Additional insights from the stakeholder integration process focused on methods to be used, with a core suggestion of adopting a multiple criteria approach, which, although not reflected in the RQs, can provide meaningful methodological guidance.

5.4.3 Design of Activities

The nature of the sustainable development agenda is such that a dedicated scenario protocol for all SDGs — in the way other tasks within WP5 explicitly develop and explore new scenario narratives — is neither the most appropriate nor the most efficient approach here. Instead, most activities in this task are built around the post-processing and analysis of thematic scenarios produced elsewhere in WP5, extracting SDG-relevant variables and characterising outcomes across the sustainable development agenda. One dedicated scenario will nonetheless be developed internally within this task, as described below.

The first step is a post-analysis of the indicators reported in MS9 and the SDG Coverage Matrix, based on the results of the baseline scenario. This will provide a structured, indicator-rich characterisation of where current climate policy ambition—as reflected in updated Nationally Determined Contributions (NDCs), the National Energy and Climate Plans (NECPs), and Long-Term Targets (LTTs)—stands in relation to the sustainable development agenda, identifying areas of synergy, tension, and gaps.

A similar approach will then be extended across selected tasks within WP5, where scenario outputs will be examined for their relevance to the sustainable development agenda. Given the clear stakeholder preference for topics related to disruptive events, a natural priority will be to draw from the scenarios developed under Task 5.3, extracting SDG-relevant variables identified in the SDG Coverage Matrix. The same approach can be applied to other thematic scenario exercises within WP5; for instance, circularity scenarios can be examined for outputs related to material use, feeding directly into an assessment of SDG 12 (Responsible Consumption and Production). This cross-task analytical layer will ensure that the SDG lens is systematically applied across the broader scenario

landscape of the project.

Beyond this broad post-analysis, the task includes two dedicated thematic deep dives that will combine scenario outputs with additional modelling steps to generate more granular SDG insights.

The first deep dive will focus on biodiversity (SDG 15: Life on Land), reflecting the clear priority expressed by stakeholders in this domain. Starting from the baseline scenario, outputs related to land use and land use change (LUC) emissions will be extracted from GCAM-Europe. These will subsequently be processed using characterisation factors derived from the Countryside species-area relationship (cSAR) model, translating land use change into a comparable biodiversity assessment indicator at the EU level. This methodological chain will allow for a quantitative characterisation of the biodiversity and land-use implications of climate mitigation pathways in the EU and at the member state level. Crucially, and in response to the fifth stakeholder research question on SDG-15-related constraints in IAM scenarios, this deep dive will also explore the implementation of a biodiversity-informed constraint within the modelling framework, examining how such a boundary condition affects scenario outcomes and model performance on this dimension.

The second deep dive will turn to heat-related health impacts in European cities (SDG 3: Good Health and Well-Being). Here, GCAM-Europe and HECTOR will be combined with the STITCHES emulator for temperature downscaling across an ensemble of four Earth System Models, paired with state-of-the-art epidemiological exposure-response functions that capture the vulnerability of different subpopulations. This setup will enable a fine-grained assessment of heat-health risks under different mitigation trajectories across European urban contexts. Analogously to the biodiversity deep dive, a boundary condition will also be explored in the form of an adaptive tree-canopy target, assessing the extent to which such a nature-based intervention can be represented within the modelling framework and its implications for health outcomes.

Finally, the task will include one internally developed scenario exercise, focused on the European context. Building on prior work exploring the SDG implications of sector-specific mitigation portfolios at the global level, a similar analytical framework will be adapted and applied at the EU scale. The exercise will connect the integrated modelling capacity developed in DIAMOND with a multi-objective optimisation approach, with the aim of evaluating how different sectoral mitigation strategies perform across key SDG dimensions, going beyond the standard least-cost optimisation logic that typically underpins IAM scenario design. The scope of the analysis will be refined as the work develops, and given the thematic deep dives described above, certain sectors or indicators may be treated at a higher level of aggregation or excluded where covered elsewhere in the task. The broader objective is to identify mitigation portfolios that are not only Paris-compliant but also better aligned with sustainable development priorities, providing policy-relevant guidance on the trade-offs and synergies inherent to the EU climate transition.

Funded by
the European Union

6 Concluding Remark

In conclusion, this report highlights the persistent challenges in fully characterising the energy-climate-economy scenario space and assessing the uncertainties embedded within both scenario development and climate assessment processes. By expanding the conceptual understanding of the scenario space, analysing uncertainties throughout the climate assessment pipeline, and introducing novel DIAMOND scenarios that incorporate stakeholder insights and enhanced model features, the report contributes to outlining the process towards expanding the scenario space and improving the robustness and comprehensiveness of scenario analysis.

References

Achakulwisut, P., Erickson, P., Guivarch, C., Schaeffer, R., Brutschin, E., & Pye, S. (2023). Global fossil fuel reduction pathways under different climate mitigation strategies and ambitions. *Nature Communications, 14*(1), 5425. doi:10.1038/s41467-023-41105-z

Al Khourdajie, A., Skea, J., & Green, R. (2024). Climate ambition, background scenario or the model? Attribution of the variance of energy-related indicators in global scenarios. *Energy and Climate Change, 5*, 100126. doi:10.1016/j.egycc.2024.100126

Amer, M., Daim, T. U., & Jetter, A. (2013). A review of scenario planning. *Futures, 46*, 23-40. doi:10.1016/j.futures.2012.10.003

Anderson, K., & Peters, G. P. (2016). The trouble with negative emissions | Science. *Science, 354*(6309), 182-183.

Bauer, N., Bertram, C., Schultes, A., Klein, D., Luderer, G., Kriegler, E., . . . Edenhofer, O. (2020). Quantification of an efficiency–sovereignty trade-off in climate policy. *Nature, 588*(7837), 261-266. doi:10.1038/s41586-020-2982-5

Beck, S., & Mahony, M. (2017). The IPCC and the politics of anticipation. *Nature Climate Change, 7*(5), 311-313. doi:10.1038/nclimate3264

Beck, S., & Oomen, J. (2021). Imagining the corridor of climate mitigation – What is at stake in IPCC's politics of anticipation? *Environmental Science & Policy, 123*, 169-178. doi:10.1016/j.envsci.2021.05.011

Bernthal, F., Dowdeswell, E., Luo, J., Attard, D., Vellinga, P., & Karimanzira, R. (1990). *Climate Change: The IPCC Response Strategies (1990)*: World Meteorological Organization, United Nations Environment Program.

Bertram, C., Brutschin, E., Drouet, L., Luderer, G., van Ruijven, B., Aleluia Reis, L., . . . Riahi, K. (2024). Feasibility of peak temperature targets in light of institutional constraints. *Nature Climate Change, 14*(9), 954-960. doi:10.1038/s41558-024-02073-4

Bornemann, B., & Christen, M. (2020). Navigating between Complexity and Control in Transdisciplinary Problem Framing: Meaning Making as an Approach to Reflexive Integration. *Social Epistemology, 34*(4), 357-369. doi:10.1080/02691728.2019.1706120

Bradfield, R., Wright, G., Burt, G., Cairns, G., & Van Der Heijden, K. (2005). The origins and evolution of scenario techniques in long range business planning. *Futures, 37*(8), 795-812. doi:10.1016/j.futures.2005.01.003

Braunreiter, L., van Beek, L., Hajer, M., & van Vuuren, D. (2021). Transformative pathways – Using integrated assessment models more effectively to open up plausible and desirable low-carbon futures. *Energy Research & Social Science, 80*, 102220. doi:10.1016/j.erss.2021.102220

Briers, S., & Vienni-Baptista, B. (2024). D2.4 – Stakeholder-informed research questions. In: DIAMOND.

Briers, S., & Vienni Baptista, B. (Forthcoming). Translating and contextualising key transdisciplinary principles: The case of an integrated assessment modelling project.

Burton, C. A., Kelley, D. I., Burke, E., Mathison, C., Jones, C. D., Betts, R. A., . . . Anderson, L. O. (2024). Fire weakens land carbon sinks before 1.5 °C. *Nature Geoscience, 17*(11), 1108-1114. doi:10.1038/s41561-024-01554-7

Böttcher, M., Adolphsen, O., Geden, O., Könneke, J., Schenuit, F., & Thielges, S. (2024). Foresight: Multilevel Climate Policy in 2030. In: Stiftung Wissenschaft und Politik (SWP).

Climate Interactive. (n.d.). C-ROADS : The C-ROADS Climate Change Policy Simulator. Retrieved from https://www.climateinteractive.org/c-roads/

Cointe, B. (2024). The AR6 Scenario Explorer and the history of IPCC Scenarios Databases: evolutions and challenges for transparency, pluralism and policy-relevance. *npj Climate Action, 3*(1). doi:10.1038/s44168-023-00075-0

Cointe, B., Cassen, C., & Nadaï, A. (2019). Organising Policy-Relevant Knowledge for Climate Action: Integrated Assessment Modelling, the IPCC, and the Emergence of a Collective Expertise on Socioeconomic Emission Scenarios. *Science & Technology Studies, 32*(4), 36-57. doi:10.23987/sts.65031

Corbera, E., Calvet-Mir, L., Hughes, H., & Paterson, M. (2015). Patterns of authorship in the IPCC Working Group III report. *Nature Climate Change, 6*(1), 94-99. doi:10.1038/nclimate2782

Cordova-Pozo, K., & Rouwette, E. A. J. A. (2023). Types of scenario planning and their effectiveness: A review of reviews. *Futures, 149*. doi:10.1016/j.futures.2023.103153

Cork, S., Alexandra, C., Alvarez-Romero, J. G., Bennett, E. M., Berbés-Blázquez, M., Bohensky, E., . . . Wyborn, C. (2023). Exploring Alternative Futures in the Anthropocene. *Annual Review of Environment and Resources, 48*(1), 25-54. doi:10.1146/annurev-environ-112321-095011

Creutzig, F., Agoston, P., Goldschmidt, J. C., Luderer, G., Nemet, G., & Pietzcker, R. C. (2017). The underestimated potential of solar energy to mitigate climate change. *Nature Energy, 2*(9). doi:10.1038/nenergy.2017.140

Cunningham, C. X., Abatzoglou, J. T., Kolden, C. A., Williamson, G. J., Steuer, M., & Bowman, D. M. J. S. (2025). Climate-linked escalation of societally disastrous wildfires. *Science, 390*(6768), 53-58. doi:DOI: 10.1126/science.adr5127

D'Orazio, P., & Valente, M. (2019). The role of finance in environmental innovation diffusion: An evolutionary modeling approach. *Journal of Economic Behavior & Organization, 162*, 417-439. doi:10.1016/j.jebo.2018.12.015

Dekker, M. M., Daioglou, V., Pietzcker, R., Rodrigues, R., de Boer, H.-S., Dalla Longa, F., . . . van Vuuren, D. (2023). Identifying energy model fingerprints in mitigation scenarios. *Nature Energy, 8*(12), 1395-1404. doi:10.1038/s41560-023-01399-1

Dellink, R., Chateau, J., Lanzi, E., & Magné, B. (2017). Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change, 42*, 200-214. doi:10.1016/j.gloenvcha.2015.06.004

Dikau, S., & Volz, U. (2018). Central Banking, Climate Change, and Green Finance. In J. Sachs, W. Woo, N. Yoshino, & F. Taghizadeh-Hesary (Eds.), Handbook of Green Finance. Singapore: Springer Singapore.

Diluiso, F., Annicchiarico, B., Kalkuhl, M., & Minx, J. C. (2021). Climate actions and macro-financial stability: The role of central banks. *Journal of Environmental Economics and Management, 110*. doi:10.1016/j.jeem.2021.102548

Elzen, B., Geels, F. W., Hofman, P. S., & Green, K. (2004). Socio-technical scenarios as a tool for transition policy: an example from the traffic and transport domain. In B. Elzen, F. W. Geels, & K. Green (Eds.), *System innovation and the transition to sustainability: Theory, evidence and policy* (pp. 251-281).

Ferrari, A., & Nispi Landi, V. (2023). Whatever it takes to save the planet? Central banks and unconventional green policy. *Macroeconomic Dynamics, 28*(2), 299-324. doi:10.1017/s1365100523000032

Fujimori, S., Krey, V., Riahi, K., Sugiyama, M., Hasegawa, T., Edmonds, J., . . . Weitzel, M. (2025). Towards an open model intercomparison platform for integrated assessment models scenarios. *Nature Climate Change, 15*(11), 1156-1164. doi:10.1038/s41558-025-02462-3

Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., . . . Yamagata, Y. (2014). Betting on negative emissions. *Nature Climate Change, 4*(10), 850-853. doi:10.1038/nclimate2392

Gambhir, A., Albert, M. J., Doe, S. S. P., Donges, J. F., Farajalla, N., Giatti, L. L., . . . Richardson, R. (2025). A systemic risk assessment methodological framework for the global polycrisis. *Nature Communications, 16*(1), 7382. doi:10.1038/s41467-025-62029-w

Geels, F. W., McMeekin, A., & Pfluger, B. (2020). Socio-technical scenarios as a methodological tool to explore social and political feasibility in low-carbon transitions: Bridging computer models and the multi-level perspective in UK electricity generation (2010–2050). *Technological Forecasting and Social Change, 151*. doi:10.1016/j.techfore.2018.04.001

Giarola, S., Chiani, L., Drouet, L., Marangoni, G., Nappo, F., Muttarak, R., & Tavoni, M. (2024). Underestimating demographic uncertainties in the synthesis process of the IPCC. *npj Climate Action, 3*(1), 1-20. doi:10.1038/s44168-024-00152-y

Grant, N., Hawkes, A., Mittal, S., & Gambhir, A. (2021). The policy implications of an uncertain carbon dioxide removal potential. *Joule, 5*(10), 2593-2605. doi:10.1016/j.joule.2021.09.004

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., . . . Valin, H. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy, 3*(6), 515-527. doi:10.1038/s41560-018-0172-6

Guivarch, C., Le Gallic, T., Bauer, N., Fragkos, P., Huppmann, D., Jaxa-Rozen, M., . . . Wagner, F. (2022). Using large ensembles of climate change mitigation scenarios for robust insights. *Nature Climate Change, 12*(5), 428-435. doi:10.1038/s41558-022-01349-x

Hahnel, U. J. J., Chatelain, G., Conte, B., Piana, V., & Brosch, T. (2020). Mental accounting mechanisms in energy decision-making and behaviour. *Nature Energy, 5*(12), 952-958. doi:10.1038/s41560-020-00704-6

Hannachi, A., Finke, K., & Trendafilov, N. (2022). Common EOFs: a tool for multi-model comparison and evaluation. *Climate Dynamics, 60*(5-6), 1689-1703. doi:10.1007/s00382-022-06409-8

Hatton, L., Staffell, I., Jansen, M., Oluleye, G., & Hawkes, A. (2025). Historical and future projected costs of capital for ten energy technologies across 176 countries. *Scientific Data, 12*(1), 1912. doi:10.1038/s41597-025-06177-0

Hausfather, Z., & Peters, G. (2020). Emissions – the 'business as usual' story is misleading. *Nature*(577), 618-620. doi:https://doi.org/10.1038/d41586-020-00177-3

Herbig, V. (2024). *From stakeholder engagement to inclusivity: Advancing participatory modeling for net-zero sustainable development: A case study of the DIAMOND Project.* (Master), Swiss Federal Institute of Technology (ETH) Zurich.

Hermansen, E. A. T., Boasson, E. L., & Peters, G. P. (2023). Climate action post-Paris: how can the IPCC stay relevant? *npj Climate Action, 2*(1), 1-8. doi:10.1038/s44168-023-00058-1

Hickel, J., Brockway, P., Kallis, G., Keyßer, L., Lenzen, M., Slameršak, A., . . . Ürge-Vorsatz, D. (2021). Urgent need for post-growth climate mitigation scenarios. *Nature Energy, 6*(8), 766-768. doi:10.1038/s41560-021-00884-9

Hoffmann, S., Deutsch, L., Klein, J. T., & O'Rourke, M. (2022). Integrate the integrators! A call for establishing academic careers for integration experts. *Humanities and Social Sciences Communications, 9*(1). doi:10.1057/s41599-022-01138-z

Hong, H., Karolyi, G. A., & Scheinkman, J. A. (2020). Climate Finance. *The Review of Financial Studies, 33*(3), 1011-1023. doi:10.1093/rfs/hhz146

Houghton, J. T., Callander, B. A., & Varney, S. K. (1992). *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*: Cambridge University Press, Cambridge, Great Britain, New York, NY, USA, and Victoria , Australia.

Huppmann, D. (2026). *Scenario Compass Initiative - Pathways Ensemble 2025*. Retrieved from: https://doi.org/10.5281/zenodo.18598251

http://dx.doi.org/10.5281/zenodo.18598251

Huppmann, D., Rogelj, J., Krey, V., Kriegler, E., & Riahi, K. (2018). A new scenario resource for integrated 1.5 °C research. *Nature Climate Change*. doi:10.1038/s41558-018-0317-4

IEA. (2025). *World Energy Outlook 2025*: Inernational Energy Agency.

IPCC. (1994). *Climate Change 1994: Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios*. Cambridge: Cambridge University Press.

IPCC. (2000). *Special Report on Emission Scenarios (SRES)*. Cambridge: Cambridge University Press.

IPCC. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Retrieved from Geneva, Switzerland:

IPCC. (2022a). Annex III: Scenarios and Modelling Methods. In *Climate Change 2022 - Mitigation of Climate Change* (pp. 1841-1908).

IPCC. (2022b). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (P. R. Shukla, J. Skea, R. Slade, A. A. Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, & J. Malley Eds.). Cambridge, UK and New York, NY, USA: Cambridge University Press.

Jaxa-Rozen, M., & Trutnevyte, E. (2021). Sources of uncertainty in long-term global scenarios of solar photovoltaic technology. *Nature Climate Change, 11*(3), 266-273. doi:10.1038/s41558-021-00998-8

Jewell, J., & Cherp, A. (2019). On the political feasibility of climate change mitigation pathways: Is it too late to keep warming below 1.5°C? *WIREs Climate Change, 11*(1). doi:10.1002/wcc.621

Jiang, L., & O'Neill, B. C. (2017). Global urbanization projections for the Shared Socioeconomic Pathways. *Global Environmental Change, 42*, 193-199. doi:10.1016/j.gloenvcha.2015.03.008

Kazlou, T., Cherp, A., & Jewell, J. (2024). Feasible deployment of carbon capture and storage and the requirements of climate targets. *Nature Climate Change, 14*(10), 1047-1055. doi:10.1038/s41558-024-02104-0

Kc, S., & Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Glob Environ Change, 42*, 181-192. doi:10.1016/j.gloenvcha.2014.06.004

Kc, S., Moradhvaj, Potancokova, M., Adhikari, S., Yildiz, D., Mamolo, M., . . . Goujon, A. (2024). *Wittgenstein Center (WIC) Population and Human Capital Projections - 2023*. Retrieved from: https://doi.org/10.5281/zenodo.14718294

http://dx.doi.org/10.5281/zenodo.14718294

Keepin, B., & Wynne, B. (1984). Technical analysis of IIASA energy scenarios. *Nature, 312*(5996), 691-695. doi:10.1038/312691a0

Kikstra, J. S., Nicholls, Z. R. J., Smith, C. J., Lewis, J., Lamboll, R. D., Byers, E., . . . Riahi, K. (2022). The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures.

Geoscientific Model Development, 15(24), 9075-9109. doi:10.5194/gmd-15-9075-2022

Koasidis, K., Nikas, A., & Doukas, H. (2023). Why integrated assessment models alone are insufficient to navigate us through the polycrisis. *One Earth, 6*(3), 205-209. doi:10.1016/j.oneear.2023.02.009

Krawczyk, F., & Braun, A. C. (2025). Models like heroes? Making Integrated Assessment Models (IAMs) ready for deep decarbonization and a socio-economic transformation. *Energy Research & Social Science, 121*. doi:10.1016/j.erss.2025.103959

Köberle, A. C., Vandyck, T., Guivarch, C., Macaluso, N., Bosetti, V., Gambhir, A., . . . Rogelj, J. (2021). The cost of mitigation revisited. *Nature Climate Change, 11*(12), 1035-1045. doi:10.1038/s41558-021-01203-6

Lahn, B., Sognnaes, I., & Hermansen, E. A. T. (2025). Analysing the use of emissions scenarios in practice. *npj Climate Action, (in review)*.

Lamboll, R. D., Nicholls, Z. R. J., Kikstra, J. S., Meinshausen, M., & Rogelj, J. (2020). Silicone v1.0.0: an open-source Python package for inferring missing emissions data for climate change research. *Geoscientific Model Development, 13*(11), 5259-5275. doi:10.5194/gmd-13-5259-2020

Lamontagne, J. R., Reed, P. M., Link, R., Calvin, K. V., Clarke, L. E., & Edmonds, J. A. (2018). Large Ensemble Analytic Framework for Consequence-Driven Discovery of Climate Change Scenarios. *Earth's Future, 6*(3), 488-504. doi:10.1002/2017ef000701

Lamperti, F., Bosetti, V., Roventini, A., Tavoni, M., & Treibich, T. (2021). Three green financial policies to address climate risks. *Journal of Financial Stability, 54*. doi:10.1016/j.jfs.2021.100875

Lang, D. J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., . . . Thomas, C. J. (2012). Transdisciplinary research in sustainability science: Practice, principles, and challenges. *Sustainability Science, 7*(SUPPL. 1), 25-43. doi:10.1007/s11625-011-0149-x

Lawrence, M. G., Williams, S., Nanz, P., & Renn, O. (2022). Characteristics, potentials, and challenges of transdisciplinary research. *One Earth, 5*(1), 44-61. doi:10.1016/j.oneear.2021.12.010

Li, P., Zhu, R., McJeon, H., Byers, E., Zhou, P., & Ou, Y. (2025). Using deep learning to generate key variables in global mitigation scenarios. *Nature Climate Change, 15*(7), 760-768. doi:10.1038/s41558-025-02352-8

Matthews, H. D., Gillett, N. P., Stott, P. A., & Zickfeld, K. (2009). The proportionality of global warming to cumulative carbon emissions. *Nature, 459*(7248), 829-832. doi:10.1038/nature08047

Mazzucato, M., & Semieniuk, G. (2018). Financing renewable energy: Who is financing what and why it matters. *Technological Forecasting and Social Change, 127*, 8-22. doi:10.1016/j.techfore.2017.05.021

McCollum, D. L., Gambhir, A., Rogelj, J., & Wilson, C. (2020). Energy modellers should explore extremes more systematically in scenarios. *Nature Energy, 5*(2), 104-107. doi:10.1038/s41560-020-0555-3

Minx, J. C., Hilaire, J., Müller-Hansen, F., Nemet, G., Diluiso, F., Andrew, R. M., . . . Wiseman, J. (2024). Coal transitions—part 2: phase-out dynamics in global long-term mitigation scenarios. *Environmental Research Letters, 19*(3), 033002. doi:10.1088/1748-9326/ad24cd

Morris, J., Hone, D., Haigh, M., Sokolov, A., & Paltsev, S. (2023). Future energy: in search of a scenario reflecting current and future pressures and trends. *Environmental Economics and Policy Studies, 25*(1), 31-61. doi:10.1007/s10018-021-00339-1

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., . . . Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment. *Nature, 463*(7282), 747-756.

doi:10.1038/nature08823

Muttitt, G., Price, J., Pye, S., & Welsby, D. (2023). Socio-political feasibility of coal power phase-out and its role in mitigation pathways. *Nature Climate Change, 13*(2), 140-147. doi:10.1038/s41558-022-01576-2

NGFS. (2024). NGFS long-term scenarios for central banks and supervisors. In: Network for Greening the Financial System.

Nikas, A., Frilingou, N., Al Khourdajie, A., & Gambhir, A. (2024). Science must up its game to support climate finance negotiations. *Nature, 636*(8041), 45-45. doi:10.1038/d41586-024-03945-7

Nikas, A., Gambhir, A., Trutnevyte, E., Koasidis, K., Lund, H., Thellufsen, J. Z., . . . Doukas, H. (2021). Perspective of comprehensive and comprehensible multi-model energy and climate science in Europe. *Energy, 215*. doi:10.1016/j.energy.2020.119153

Nikas, A., Xexakis, G., Koasidis, K., Acosta-Fernández, J., Arto, I., Calzadilla, A., . . . Doukas, H. (2022). Coupling circularity performance and climate action: From disciplinary silos to transdisciplinary modelling science. *Sustainable Production and Consumption, 30*, 269-277. doi:10.1016/j.spc.2021.12.011

Norström, A. V., Cvitanovic, C., Löf, M. F., West, S., Wyborn, C., Balvanera, P., . . . Österblom, H. (2020). Principles for knowledge co-production in sustainability research. *Nature Sustainability, 3*(3), 182-190. doi:10.1038/s41893-019-0448-2

O'Neill, B. C., Carter, T. R., Ebi, K., Harrison, P. A., Kemp-Benedict, E., Kok, K., . . . Pichs-Madruga, R. (2020). Achievements and needs for the climate change scenario framework. *Nature Climate Change, 10*(12), 1074-1084. doi:10.1038/s41558-020-00952-0

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., . . . Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change, 42*, 169-180. doi:10.1016/j.gloenvcha.2015.01.004

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., . . . Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development, 9*, 3461-3482. doi:10.5194/gmd-9-3461-2016

Pedersen, J. S. T., Duarte Santos, F., van Vuuren, D., Gupta, J., Encarnação Coelho, R., Aparício, B. A., & Swart, R. (2021). An assessment of the performance of scenarios against historical global emissions for IPCC reports. *Global Environmental Change, 66*, 102199. doi:10.1016/j.gloenvcha.2020.102199

Pedersen, J. S. T., van Vuuren, D., Gupta, J., Santos, F. D., Edmonds, J., & Swart, R. (2022). IPCC emission scenarios: How did critiques affect their quality and relevance 1990–2022? *Global Environmental Change, 75*, 102538. doi:10.1016/j.gloenvcha.2022.102538

Peng, W., Iyer, G., Bosetti, V., Chaturvedi, V., Edmonds, J., Fawcett, A. A., . . . Weyant, J. (2021). Climate policy models need to get real about people — here's how. *Nature, 594*(7862), 174-176. doi:10.1038/d41586-021-01500-2

Pereira, L. M., Morrow, D. R., Aquila, V., Beckage, B., Beckbesinger, S., Beukes, L., . . . Trisos, C. H. (2021). From fAIrplay to climate wars: making climate change scenarios more dynamic, creative, and integrative. *Ecology and Society, 26*(4). doi:10.5751/es-12856-260430

Peters, G. P., Al Khourdajie, A., Sognnaes, I., & Sanderson, B. M. (2023). AR6 scenarios database: an assessment of current practices and future recommendations. *npj Climate Action, 2*(1), 1-6. doi:10.1038/s44168-023-00050-9

Peters, G. P., Andrew, R. M., Solomon, S., & Friedlingstein, P. (2015). Measuring a fair and ambitious climate agreement using cumulative emissions. *Environmental Research Letters, 10*(10). doi:10.1088/1748-

9326/10/10/105004

Pye, S., Broad, O., Bataille, C., Brockway, P., Daly, H. E., Freeman, R., . . . Watson, J. (2021). Modelling net-zero emissions energy systems requires a change in approach. *Climate Policy, 21*(2), 222-231. doi:10.1080/14693062.2020.1824891

Ram, M., Osorio-Aravena, J. C., Aghahosseini, A., Bogdanov, D., & Breyer, C. (2022). Job creation during a climate compliant global energy transition across the power, heat, transport, and desalination sectors by 2050. *Energy, 238*, 121690. doi:10.1016/j.energy.2021.121690

Riahi, K., Bertram, C., Huppmann, D., Rogelj, J., Bosetti, V., Cabardos, A.-M., . . . Zakeri, B. (2021). Cost and attainability of meeting stringent climate targets without overshoot. *Nature Climate Change, 11*(12), 1063-1069. doi:10.1038/s41558-021-01215-2

Riahi, K., Schaeffer, R., Arango, J., Calvin, K., Guivarch, C., Hasegawa, T., . . . Van Vuuren, D. P. (2022). Mitigation pathways compatible with long-term goals. In. J. S. P.R. Shukla, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (Series Ed.), In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press, . doi:10.1017/9781009157926.005

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., . . . Tavoni, M. (2017). 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

Roe, S., Streck, C., Obersteiner, M., Frank, S., Griscom, B., Drouet, L., . . . Lawrence, D. (2019). Contribution of the land sector to a 1.5 °C world. *Nature Climate Change, 9*(11), 817-828. doi:10.1038/s41558-019-0591-9

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., . . . Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change, 8*(4), 325-332. doi:10.1038/s41558-018-0091-3

Schweizer, V. J., & O'Neill, B. C. (2013). Systematic construction of global socioeconomic pathways using internally consistent element combinations. *Climatic Change, 122*(3), 431-445. doi:10.1007/s10584-013-0908-z

Skea, J., Shukla, P., Al Khourdajie, A., & McCollum, D. (2021). Intergovernmental Panel on Climate Change: Transparency and integrated assessment modeling. *WIREs Climate Change, 12*(5), e727. doi:10.1002/wcc.727

Skea, J., van Diemen, R., Portugal-Pereira, J., & Khourdajie, A. A. (2021). Outlooks, explorations and normative scenarios: Approaches to global energy futures compared. *Technological Forecasting and Social Change, 168*. doi:10.1016/j.techfore.2021.120736

Sognnaes, I., Gambhir, A., van de Ven, D.-J., Nikas, A., Anger-Kraavi, A., Bui, H., . . . Peters, G. P. (2021). A multi-model analysis of long-term emissions and warming implications of current mitigation efforts. *Nature Climate Change, 11*(12), 1055-1062. doi:10.1038/s41558-021-01206-3

Sognnaes, I., & Peters, G. (2025). Influence of individual models and studies on quantitative mitigation findings in the IPCC Sixth Assessment Report. Retrieved from https://www.researchsquare.com/article/rs-5698716/v1 doi:https://doi.org/10.21203/rs.3.rs-5698716/v1

Sovacool, B. K., Ali, S. H., Bazilian, M., Radley, B., Nemery, B., Okatz, J., & Mulvaney, D. (2020). Sustainable minerals and metals for a low-carbon future. *Science, 367*(6473), 30-33. doi:10.1126/science.aaz6003

TCFD. (2017). *Recommendations of the Task Force on Climate-related Financial Disclosures*. Retrieved from

https://assets.bbhub.io/company/sites/60/2021/10/FINAL-2017-TCFD-Report.pdf

Thompson, E. (2022). *Escape from model land: How mathematical models can lead us astray and what we can do about it.*: Basic Books.

van Beek, L., Hajer, M., Pelzer, P., van Vuuren, D., & Cassen, C. (2020). Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970. *Global Environmental Change, 65*, 102191. doi:10.1016/j.gloenvcha.2020.102191

van Beek, L., Oomen, J., Hajer, M., Pelzer, P., & van Vuuren, D. (2022). Navigating the political: An analysis of political calibration of integrated assessment modelling in light of the 1.5 °C goal. *Environmental Science & Policy, 133*, 193-202. doi:10.1016/j.envsci.2022.03.024

van Ruijven, B. J. (2016). Mind the gap – the case for medium level emission scenarios. *Climatic Change, 138*(3), 361-367. doi:10.1007/s10584-016-1744-8

van Soest, H. L., Aleluia Reis, L., Baptista, L. B., Bertram, C., Després, J., Drouet, L., . . . van Vuuren, D. P. (2021). Global roll-out of comprehensive policy measures may aid in bridging emissions gap. *Nature Communications, 12*(1), 6419. doi:10.1038/s41467-021-26595-z

van Tilburg, R., & Simić, A. (2021). Every Avenue Available: Lessons from Monetary History for Tracking Climate change *Sustainable Finance Lab*. Retrieved from

van Vuuren, D. P., Hof, A. F., van Sluisveld, M. A. E., & Riahi, K. (2017). Open discussion of negative emissions is urgently needed. *Nature Energy, 2*(12), 902-904. doi:10.1038/s41560-017-0055-2

van Vuuren, D. P., Kriegler, E., O'Neill, B. C., Ebi, K. L., Riahi, K., Carter, T. R., . . . Winkler, H. (2013). A new scenario framework for Climate Change Research: scenario matrix architecture. *Climatic Change, 122*(3), 373-386. doi:10.1007/s10584-013-0906-1

van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., van den Berg, M., Bijl, D. L., de Boer, H. S., . . . van Sluisveld, M. A. E. (2018). Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change, 8*(5), 391-397. doi:10.1038/s41558-018-0119-8

Vienni-Baptista, B., Fletcher, I., Lyall, C., & Pohl, C. (2022). Embracing heterogeneity: Why plural understandings strengthen interdisciplinarity and transdisciplinarity. *Science and Public Policy, 49*(6), 865-877. doi:10.1093/scipol/scac034

Wilbanks, T. J., & Ebi, K. L. (2014). SSPs from an impact and adaptation perspective. *Climatic Change, 122*(3), 473-479. doi:10.1007/s10584-013-0903-4