Global Environmental Change 75 (2022) 102538

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

IPCC emission scenarios: How did critiques affect their quality and relevance 1990–2022?

Jiesper Tristan Strandsbjerg Pedersen[a,b,*], Detlef van Vuuren[c,d,*], Joyeeta Gupta[e,h], Filipe Duarte Santos[a], Jae Edmonds[f], Rob Swart[a,g]

[a] *Climate Change Impacts, Adaptation and Modelling (CCIAM), Centre for Ecology, Evolution and Environmental Changes (cE3c), Faculty of Sciences of the University of Lisbon, Portugal*
[b] *Social Science Institute (ICS-UL) of the University of Lisbon, Portugal*
[c] *PBL Netherlands Environmental Assessment Agency, Den Hague, the Netherlands*
[d] *Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, the Netherlands*
[e] *Governance and Inclusive Development; Geography, Planning and International Development Studies; AISSR; University of Amsterdam, The Netherlands*
[f] *PNNL Pacific Northwest National Laboratory, Joint Global Change Research Institute, United States*
[g] *Wageningen Environmental Research, Wageningen, the Netherlands*
[h] *IHE Delft Institute for Water Education, Delft, The Netherlands*

ARTICLE INFO

Keywords:
Emission scenario generations
Intergovernmental Panel on Climate Change (IPCC)
Literature assessments and critiques
Emission scenario evolution & developments
Emission scenario characteristics and exercises

ABSTRACT

Long-term global emission scenarios enable the analysis of future climate change, impacts, and response strategies by providing insight into possible future developments and linking these different climate research elements. Such scenarios play a crucial role in the climate change literature informing the Intergovernmental Panel on Climate Change's (IPCC) Assessment Reports (ARs) and support policymakers. This article reviews the evolution of emission scenarios, since 1990, by focusing on scenario critiques and responses as published in the literature. We focus on the issues raised in the critiques and the possible impact on scenario development. The critique (280) focuses on four areas: 1) key scenario assumptions (40%), 2) the emissions range covered by the scenarios and missing scenarios (25%), 3) methodological issues (24%), and 4) the policy relevance and handling of uncertainty (11%). Scenario critiques have become increasingly influential since 2000. Some areas of critique have decreased or become less prominent (probability, development process, convergence assumptions, and economic metrics). Other areas have become more dominant over time (e.g., policy relevance & implications of scenarios, transparency, Negative Emissions Technologies (NETs) assumptions, missing scenarios). Several changes have been made in developing scenarios and their content that respond to the critique.

1. Introduction

Because climate change and its impacts extend into the distant future (IPCC, 1990a; O'Neill et al., 2017), long-term global (emission) scenarios have influenced climate research and assessments for at least 30 years (van Beek et al., 2020; van Vuuren et al., 2012). These scenarios are projections of future greenhouse gasses (GHG), air pollutants and aerosols, and future land use based on underlying projections for energy and food systems (Riahi et al., 2017). The output of emission scenarios (emissions) is used as input for 1) climate change research, 2) impact

Abbreviations: AR1, IPCC First Assessment Report (AR2 = Second Assessment Report); BECCS, Bioenergy with Carbon Capture and Storage; CCS, Carbon Capture and Storage; COPs, Conferences of the Parties (under the UNFCCC); GHGs, Greenhouse Gasses; IAMs, Integrated Assessment Models; IPCC, Intergovernmental Panel on Climate Change; NETs, Negative Emissions Technologies; UNFCCC, United Nations Frmework Convention on Climate Change; SA90, Scientific Assessments 1990 (first generation of scenarios informing IPCC assessment reports); IS92, IPCC Scenarios 1992 (2nd scenario generation); SRES, Special Report on Emission Scenarios (3rd generation); RCPs, Representative Concentration Pathways (4th generation - emission pathways); SPAs, Shared Policy Assumptions (4th generation - policy assumptions); SSPs, Shared Socioeconomic Pathways (4th generation - storylines); Post-SRES, SRES mitigation scenarios published and analyzed in IPCC AR3; Intervention scenarios, Scenarios including mitigation policy assumptions (also called mitigation scenarios); Baselines, Scenarios not including mitigation policy assumptions; Convergence, Scenarios describing increased world equality (often via GDP/income).

* Corresponding authors at: CCIAM, Faculdade de Ciências da Universidade de Lisboa (FCUL) Campo Grande, Edifício C1, 2.39, 1749-016 Lisboa, Portugal.
E-mail addresses: jiespertristan@gmail.com (J.T.S. Pedersen), D.P.vanVuuren@uu.nl (D. van Vuuren).

https://doi.org/10.1016/j.gloenvcha.2022.102538
Received 28 September 2021; Received in revised form 28 April 2022; Accepted 11 May 2022
Available online 6 June 2022

assessment, and finally, 3) mitigation analysis. Thus, these scenarios play a key role in linking different climate research disciplines (IPCC, 2014a, 1990b), the Intergovernmental Panel on Climate Change's (IPCC) assessment reports (ARs), and have supported national and international policymaking, reflected in the Paris Agreement on Climate Change (UNFCCC/COP, 2015), and referred to in national climate pledges (UNFCCC, 2021) and policies (Baranzelli et al., 2013; Fawcett et al., 2015). Additionally, emissions scenarios enable the assessment of the effectiveness of the Paris Agreement (UNEP, 2020), represent a crucial feature defining future sustainability thinking (Otero et al., 2020), and the need and range of possible sustainable development policy actions (Raskin et al., 2005).

Developing scenarios is not straightforward. They are typically created through qualitative assumptions and quantifications using integrated assessment models (IAMs). They require projections of underlying human activity levels over the long term (van Vuuren et al., 2010) and complex methodologies to significantly discern scenario differences within a framework (Schweizer and O'Neill, 2014). Thus, assessments need to be made on possible future changes for many factors such as socioeconomic development, technology advances, and lifestyle change (O'Neill et al., 2017). Similar choices are made on focus areas and definitions (Raskin and Swart, 2020).

The prominent role and the uncertainties and (subjective) choices involved in the work have led to multiple critiques caused by factors such as changing contexts and roles (Girod et al., 2009; Moss et al., 2010), different worldviews (Parikh, 1992; Schneider, 2001), methodological advances (Schweizer and Kriegler, 2012), and model-focused method-assessments by scenario developers/modelers (Schweizer and O'Neill, 2014). There has been quite some literature on the critique, assessments, and responses. However, no attempt has been made to assess the critique systematically. This paper provides the first comprehensive overview of emission scenario critiques, their responses, and possible impact on the scenarios and scenario developments. The review focuses on the scenarios informing the IPCC assessment reports 1990–2022, as these are also the most prominent scenarios in the scientific literature and policy assessment (O'Neill et al., 2020; Wilkinson and Eidinow, 2008). The history of IPCC assessments covers four generations of emissions scenarios. Three series were developed inside the IPCC, comprising the "1990 IPCC First Scientific Assessment" (SA90), (IPCC, 1990a), the "1992 IPCC Scenarios" (IS92) (Leggett et al., 1992), and the 2000 "Special Report on Emissions Scenarios" (SRES) (Nakicenovic and Swart, 2000), and the additional Post-SRES including intervention (IPCC, 2001a). The most recent emissions scenarios were developed outside the IPCC (Moss et al., 2010), i.e., the "Representative Concentration Pathways" (RCPs) (van Vuuren et al., 2011) and the "Shared Socioeconomic Pathways" (SSPs) (O'Neill et al., 2014; Riahi et al., 2017). The RCPs informed AR5, while the SSP-RCP combinations informed AR6 (IPCC, 2021). This paper does not analyze the scenarios but explores how others have evaluated and perceived the art of emission scenario development in an IPCC context, including the four subsequent emissions scenario series that have informed IPCC assessments (Moss et al., 2010; van Vuuren and O'Neill, 2006). This paper aims to neutral reflect the critique in line with a review paper. It does not judge the quality or content of critiques. Nor do we focus on the hundreds of scenarios published by IAM groups individually, the work of EMF (EMF, 2020), or the IEA World Energy Outlook. At the same time, a considerable part of the discussion in this paper is also relevant to the broader scenario literature.

2. Methods

The listed 'scenario critiques' comprise peer-reviewed critiques and responses that communicate 'critically' reflective analyses of the current scenario (practice) that criticize or defend the four generations of (IPCC) emission scenarios. Some papers assessed, discerned (e.g., Webster et al., 2002), or judged the scenarios (e.g., Parikh, 1992). Others evaluated the scenarios (e.g., Manne et al., 2005) based on initial critiques (Castles and Henderson, 2003a). Scenario developers/modelers (Grübler and Nakicenovic, 2001) and others (Dessai and Hulme, 2004) responded to critiques, participated in debates, and sometimes reshaped the scenarios.

First, we conducted a systematic literature search. Relevant peer-reviewed critical literature and responses were identified via IPCC Assessments (e.g., IPCC, 2001a), primary scenario literature, and their bibliographies (e.g., Nakicenovic and Swart, 2000), SCOPUS, Google, and Google Scholar database searches. The search terms included all combinations presented in Fig. 1. We selected literature critiques or papers presenting scenario improvements, and responses to critiques by reading titles, abstracts, introductions, conclusions, and the full text. We also reviewed the relevant references in the papers. The listed papers may not be complete, but the method provides a solid basis for assessing the main critique topics (Table 1), their evolution, and contribution (SI Tables 1 and 2).

Second, we categorized papers based on their focus: 1) scenario assumptions, 2) scenario range, 3) methodological issues, and 4) scenario relevance. Within each category, we identified thirteen subcategories (Table 1). In addition, each paper was classified based on its primary and secondary topics: primary topic (value = 1) and secondary topics "closely related to or a consequence of primary topic" (0.75), "supporting but having a less close relationship to the primary topic/key message" (0.5), and "additional topics with an arbitrary relationship to the primary topic" (0.25). See totals in Fig. 5.

3. Emission scenarios in the context of IPCC

Since 1990, four generations of emission scenarios have served as input to climate models and scenario-based literature informing successive IPCC Assessment Reports' (ARs) review of possible future climate change, impacts, and response strategies (IPCC, 1990a; Moss et al., 2010). Grounded in Working Group III (WG3, mitigation), emission scenarios are used by scientists in WG1 (climate science) and WG2 (impacts and adaptation) communities to analyze future outlooks – cutting across the three IPCC WGs (IPCC, 2014b, 1989a). The SA90 scenarios were used directly for analyses in all AR1 WGs. Over time scenarios were more frequently analyzed in peer-reviewed literature informing IPCC assessments rather than being analyzed by IPCC authors.

IPCC WG3 facilitated the first three series, following IPCC procedures (Bolin, 2007; IAC, 2010). The first (SA90) was developed via scientific considerations (IPCC, 1990a, IPCC, 1989b). The second (IS92) and third (SRES) series were designed under explicit intergovernmental mandates (Leggett et al., 1992; Nakicenovic and Swart, 2000) adopted in IPCC sessions. Between 2003 and 2006, the IPCC intergovernmental sessions decided to move scenario development outside the IPCC, leading to the fourth emission scenario generation (SSP-RCP). It was organized by IPCC but developed by the scientific community without constraining intergovernmental mandates. It was in line with the IPCC's aim to assess existing scientific knowledge (IPCC, 2006) rather than generate new data (Moss et al., 2010).

3.1. The four generations

The SA90s informed IPCC AR1 (IPCC, 1990a). They were developed between 1989 and 1990, led by the United States Environmental Protection Agency (USEPA) and the Dutch Environment Ministry (IPCC,

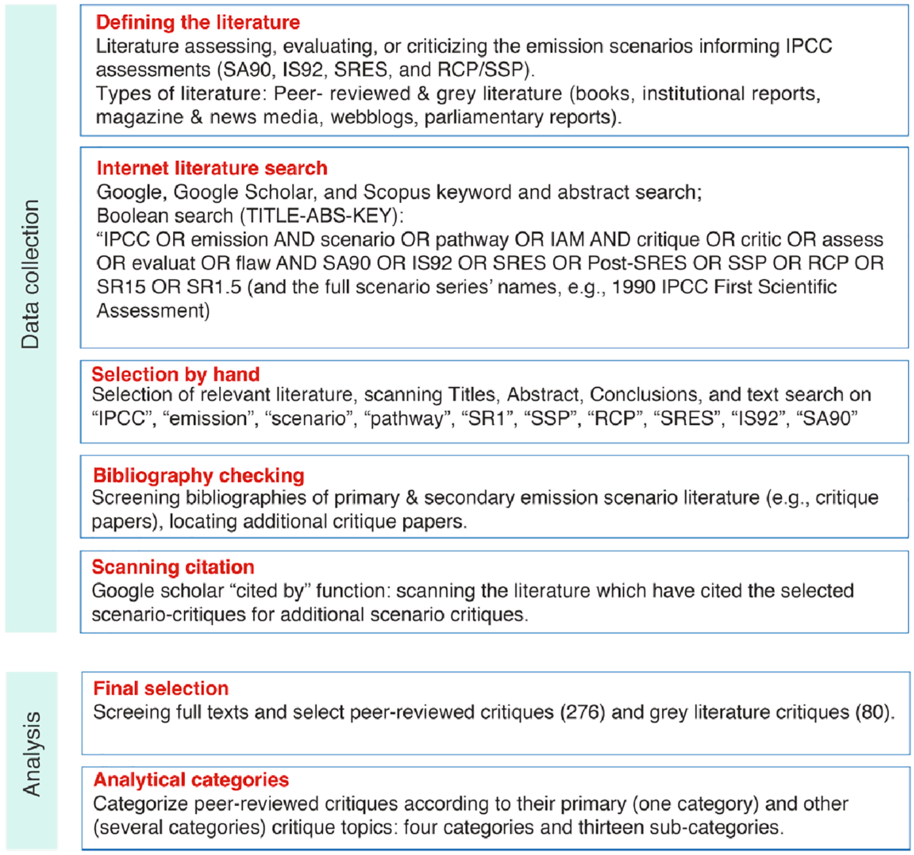

Fig. 1. Methodology. Literature search, data collection/paper selection, and categorization/analysis of critique topics.

1990a). The IPCC was newly established by country delegates primarily from Environment Ministries. The contextual framing was that climate change is a real risk: the report aimed to explore emissions pathways and what can be done (Bolin, 2007). The scenarios comprised five GHGs and were constructed via two models, the USEPA's Atmospheric Stabilization Framework (ASF) supplemented by the Dutch Integrated Model for the Greenhouse Effect (IMAGE) (IPCC, 1990a, 1990c).[1] The four marker scenarios described a high emission (no-change) pathway called Business-as-Usual (BaU) (SA90-A), slow emissions growth via changed energy mix/efficiency (SA90-B), and two mitigation policies scenarios (SA90-C/D). An uncertainty range was defined by eight scenario variants describing higher and lower economic growth (IPCC, 1990a).

The IS92 informed AR2 (1995). They were an SA90-update, developed by the same models and team, which now also included economists. The period marked a political context shift. Two key parties debated opposing views with the Climate Convention adopted in 1992 (UNFCCC, 1992). The US[2] proposed an economic target-and-timetable approach to policy, while the EU delegation believed in a science-based-target approach, starting mitigation without fully understanding the problem (Bolin, 2007; Hecht and Tirpak, 1995; Oberthür and Ott, 1999). Intergovernmental delegates changed from environmental to more powerful departments within IPCC sessions. They asked new fundamental questions about climate change's reality and mitigation costs (Hecht and Tirpak, 1995; IPCC, 1990d). Several delegations, including the US[3], argued that mitigation was premature. The session mandate (IPCC, 1991) excluded policy assumptions and higher emissions range (Edmonds et al., 1992; Pepper et al., 1992). The series included the full suite of GHGs (Alcamo et al., 1995; IPCC, 1996), more regional detail, and more diverse economy and population developments (IPCC, 1990a; Pepper et al., 1992). The series includes two high emission (IS92e/f), two low-emission (IS92c/d), and two no-change scenarios (IS92a/b) succeeding the SA90-A BaU (Leggett et al., 1992; Pepper et al., 1992).

The SRES was developed between 1996 and 1999 (IPCC, 1996; Nakicenovic and Swart, 2000). It informed AR3 (2001) and AR4 (2007), and phase 3, while RCPs and SSPs would inform Phase 5 and 6 of the Climate Model Intercomparison Project (CMIP3/5/6) (O'Neill et al., 2016). It was developed via five integrated assessment models (IAMs), scientifically recommended, and mandated by IPCC sessions. The IPCC mandate continued and became more detailed (IPCC, 2006, 2005a, 1996, 1991, IPCC, 1989b), describing a significant expansion of the development and author team - including economic stakeholder institutions, experts from various disciplines, and world regions (IPCC, 1996, 1995). In the SRES, scenario assumptions were changed to narrative families. Four storylines (A1, A2, B1, and B2) represent two dimensions: economic (A) or environmental (B) concerns and global (1) or regional development (2) patterns (Nakicenovic and Swart, 2000). The scenarios were grouped according to their cumulative CO_2

[1] The ASF framework included four integrated modules (energy, industry, agriculture, and land-use) and, additionally, an ocean model for heat and carbon uptake and an atmospheric composition module measuring the global radiation balance for temperature projections. The five categories of GHGs are comprised of 1. CO_2, 2. Methane (CH_4), 3. nitrous oxide (N_2O), 4. chlorofluorocarbons (CFC), and the CFC substitute hydrochlorofluorocarbons (HCFCs), 5. Carbon Oxide (CO) and NOx (IPCC, 1990c, 1990a, 1989a).

[2] Resistance towards climate mitigation was observed "from the energy industry, the US Senate, and Republican congressmen" in the United States (Bolin, 2007). During the 1982-1994 period, US officials were worried about the cost of an energy transition and favored less government regulation (Hecht and Tirpak, 1995).

[3] E.g., the US, OPEC, and Russia.

Table 1
Four main categories (and 13 subcategories) of emission scenario critique topics.

No.	Scenario critique topic
1	**Scenario assumptions** 1.1 Energy system assumptions (resources, PV costs, technology, etc.) 1.2 Negative Emissions Technologies (NETs) 1.3 Economic variable (MER-PPP) 1.4 Various assumptions (within a scenario, e.g., Income convergence, policy)
2	**Range of emission scenarios** (including missing scenarios) 2.1 Emissions, GDP, energy, etc. ranges - Too high - Too low 2.2 Missing scenario narratives - Aspects not included, e.g., missing degrowth, regional sustainability, climate impact feedback, climate policy)
3.	**Methodological issues** 3.1 Scenario Development Process - IPCC critique, e.g., knowledge monopoly, too much in-crowd - Writing team is too narrow - Too little or too much stakeholder involvement, democracy, etc. - Boundary objects - Wrong tool, Unreliable (the future is unknown) 3.2 Method - Integrated Assessment Models (IAMs) are not useful (economic tools) - Storyline/narrative diversity (quantifications) - Scenario framework 3.3 Transparency - Scenarios are black boxes; too little transparency 3.4 Resolution - Too little spatial resolution (energy systems, land-use, etc.)
4.	**Scenario relevance** 4.1 User/Policy implications - Not scientific; unreliable to guide policy 4.2 User/Policy relevance - Aspects needed to increase policy-relevance - Scenarios are not addressing the right questions 4.3 Role of scenarios (scenario type) - Explorative (storyline/quantification) vs. probabilistic approaches (frequency distributions) vs. Qualitative best-guess scenarios

emissions 1990–2100: B1/low emissions, B2/medium–low, A1B/medium–high, and A2/high (IPCC, 2000a). Two illustrative scenarios (A1T/low and A1FI/high) additionally explore the rapid growth family - suggested by the US delegation during the review process (Girod and Mieg, 2008; IPCC, 2000b). Compared to the previous series, technology was considered as important as population and economic development (Nakicenovic and Swart, 2000), changing low-emissions assumptions and quantifications, introducing economic growth as an alternative pathway to reducing emissions as achieved by technology advances (SRES-A1T) or structural change (SRES-B1) (Pedersen et al., 2021). The SRES did not explore mitigation scenarios, but AR3 did via the post-SRES (IPCC, 2001a).

The SSP-RCP framework was developed in a parallel process. It comprised the Representative Concentration Pathways (RCP) expressing radiative forcing scenarios (van Vuuren et al., 2011), the Shared Policy Assumptions (SPA), describing climate policy developments (Kriegler et al., 2014), and the Shared Socioeconomic Pathways (SSPs), describing socioeconomic developments (Riahi et al., 2017). In addition, an IPCC special report presented four scenarios exploring 1.5 °C pathways (SR1.5) (IPCC, 2018a) requested by the Conference of the Parties to the Climate Convention (UNFCCC/COP) to guide the Paris Agreement goals (IPCC, 2018b; Kriegler et al., 2017). IPCC sessions encouraged the inclusion of organizations with scenario experiences in development processes (IPCC, 2006). **The RCPs** informed AR5 (2013–2014). **With** more elaborated socioeconomic assumptions, the SSP-RCP combinations informed AR6 (IPCC, 2021). The 7 + 2 SSP-RCP combinations (O'Neill et al., 2016) explore radiative forcings by 2100 (RCPs) via five SSP narratives with and without policy (SPAs) (O'Neill et al., 2014; Riahi et al., 2017). The scenarios were inspired by the SRES, reflected the full scientific scenario literature (IPCC, 2007a), and were organized according to socioeconomic mitigation and adaptation challenges (Riahi et al., 2017). The IPCC constrained no meetings or reports (IPCC, 2007a; Weyant et al., 2009). The SSP-RCP low emission scenarios introduced the concept of negative emissions technologies (NETs) extracting carbon emissions from the atmosphere (Fuss et al., 2014).

Supplementary Information (SI) Tables 1 and 2 present overviews of the contemporary scientific and political context of the emission scenario generations, the scenario series' objectives, and the scientific and policy questions they generated.

3.2. The IPCC context

Fig. 2 illustrates the scenario development periods (dashed horizontal lines) and the periods of their inclusion in the scenario-based literature informing IPCC working groups (colored horizontal lines). Often impact (red line) assessment literature was the last to include the newest scenarios. For instance, IS92 informed scenario-based literature included in WG1 (green line) and WG3 (blue line) until AR3 (2001), while it continued in WG2 (red line) until AR4 (2007).

The scenario development periods have increased over time, spanning from about one year (SA90, IS92), three years (SRES), six (RCPs), to 13–15 years (SSP-RCPs). Furthermore, the process has grown more complex, implying increasing variables, disciplines, researchers, stakeholders, and more complex methods and assumptions. Simultaneously, more scenarios are produced in the scientific community and energy sector, making the current literature review process more complex than the SA90 and IS92 periods.

Fig. 3 presents the four scenario generations' key characteristics and changes over time. The figure includes convergence scenarios, which are not an essential characteristic but highlighted because it is addressed in several critiques. The emissions ranges (upper and lower levels) have expanded over time, while there is high continuity in GDP and energy emission driver ranges across the four generations (Fig. 3b). Interestingly, the SSP-RCPs' low-end emissions range is below the SA90. Despite not having explicit descriptions of climate policy, the IS92 and SRES low emission pathways (IS92c and SRES-B1/A1T) have quantifications like the SA90C/D and SSP1-2.6 low-emission policy scenarios.

4. Overall critique topics and timeline

We identified 280 peer-reviewed emissions scenario critiques and responses, and selected 80 grey literature publications (Fig. 4). Critiques intensified with the publication of the SRES, with 93% of peer-reviewed critiques published after 2000.

Over time, several biases might influence the graph, including the increasing number of papers published and plausible earlier publications that are difficult to trace in 2022. Still, we believe that the first scenario set received little critique. During the 1990s, several critiques addressed model methodology (e.g., Oreskes et al., 1994). In the past decade, several critiques addressed IAMs (Bellamy and Healey, 2018) without addressing the IPCC scenarios and are thus not included.

Fig. 5a shows that most peer-reviewed critiques addressed assumptions (40%) as their primary focus, and additionally, scenario ranges (25%), methodology (24%), and scenario user relevance, comprising policy relevance, policy implications, and probability critique (11%). Almost all critiques (78%) addressed assumptions as primary or secondary topics, while 66%, 48%, and 40% addressed scenario ranges, relevance, and methods, respectively. Policy relevance and implications were crosscutting issues often related as secondary topics to assumptions and/or range critiques. Method critiques were the least cross-cutting topic, primarily addressed as a scientific issue rather than a (politically) heated topic, and were seldom replicated in public media.

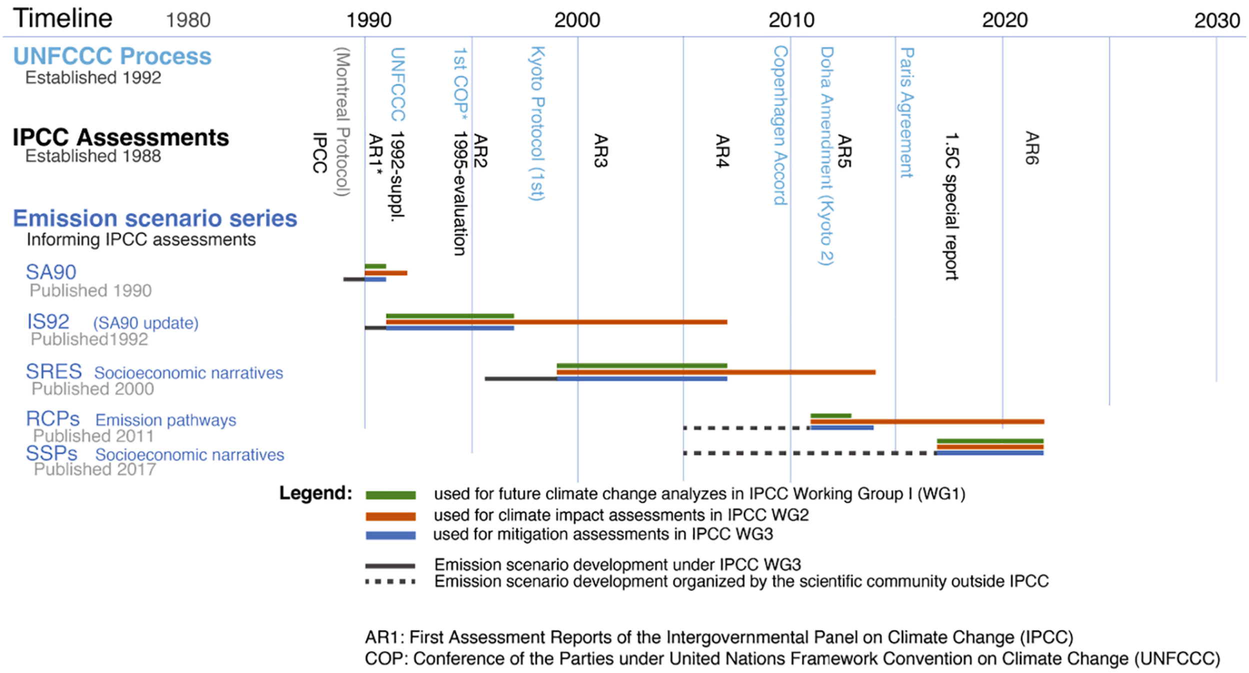

Fig. 2. Historical overview of United Nations Framework Convention on Climate Change (UNFCCC) history and key processes, Intergovernmental Panel on Climate Change establishment and assessment reports (IPCC ARs), and the four generations of emission scenario series and their inclusion in scenario-based literature informing IPCC ARs three Working Groups. Data sources: IPCC ARs 1990–2022.

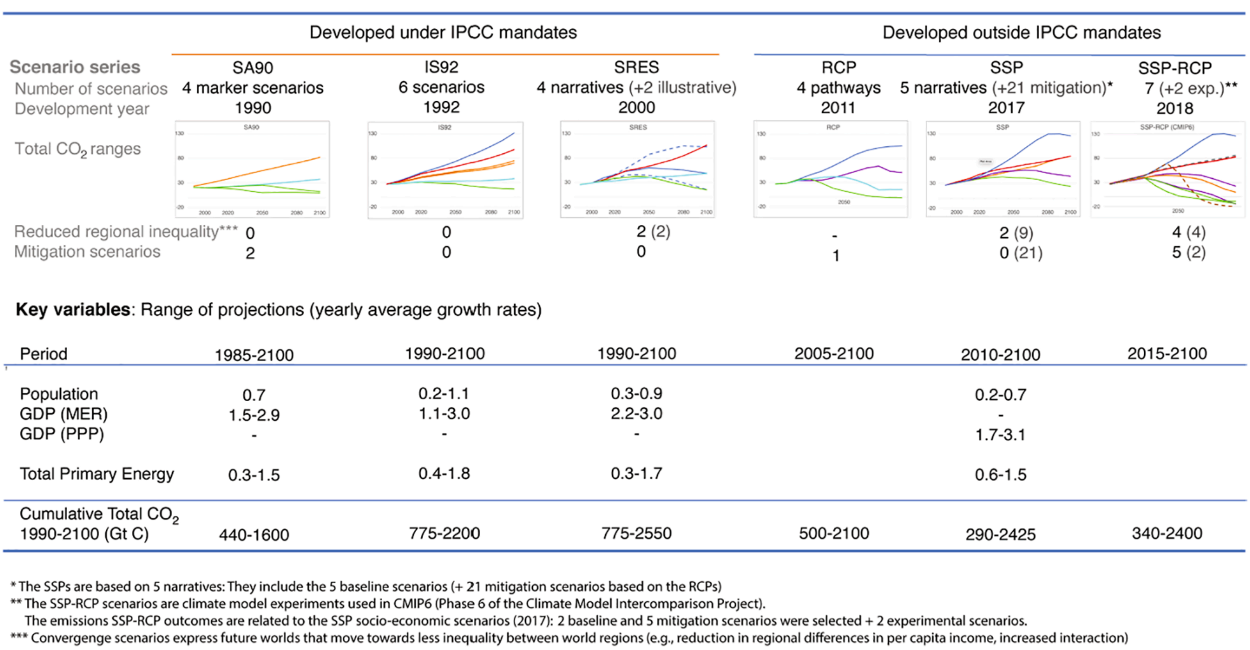

Fig. 3. Emission scenario characteristics for the four generations of emission scenario series SA90, IS92, SRES, and RCP/SSP. **a** Publication, CO_2 emission ranges, and arbitrary assumption aspects related to critiques. **b** Ranges of projections for critical variables. Data sources: Scenario databases for SA90, IS92, SRES, RCP, SSP (See SI Chapter 4), Gidden et al. (2018), and IPCC (2005b).

Several critique topics have persisted for three decades, like assumptions on energy and emission ranges (Fig. 5b). Over time, more scientific attention was drawn to scenarios (Fig. 4). Resolution critiques emerged with the SRES and storyline method assessments during RCP/SSP preparations. Other topics, like MER-PPP, probability, and IPCC in-crowd (process) critiques, have decreased or disappeared. However, qualitative likelihood critiques (i.e., identify best-guess scenarios) have recently emerged as secondary topics (Hausfather and Peters, 2020). Finally, some critiques have become more important, like methods applied, policy implications, negative emission technologies (NETs) assumptions, and missing scenarios critiques.

5. Key scenario critiques

This section presents the critiques in more detail.

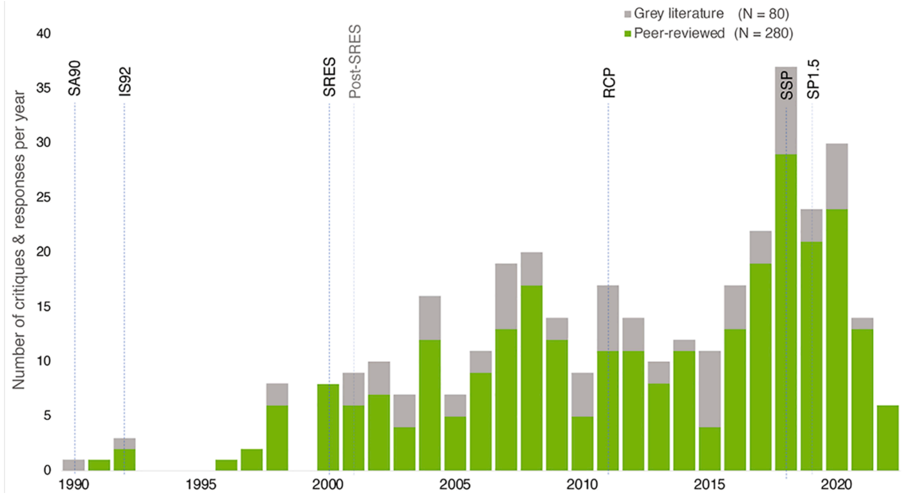

Fig. 4. Historical development and weight of scenario critique 1990–2022: Peer-reviewed (green) and grey literature (grey) critiques of emissions scenarios in the IPCC context. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.1. Assumptions

5.1.1. Income convergence

The most impactful IS92-critique addressed a limited development worldview. It emphasized an assumed growing inequality between the global South and North in the IS92a (continuation-of-historical-trends) scenario (Parikh, 1992). For the IS92 (and SA90), the regional level scenarios were less developed (IPCC, 1990a), and thus global (in-)equality assumptions were less explicit. Technically, the critique resulted in an explicit global convergence narrative principle in the third (SRES) and fourth (SSP) generations (Nakicenovic and Swart, 2000; Riahi et al., 2017). Methodologically, the critique led to an IPCC scenario evaluation, encouraging a more inclusive scenario design process (Alcamo et al., 1995), leading to the IPCC panel mandating the inclusion of non-Annex-I developing country researchers and stakeholders in the successive scenario developments (IPCC, 1996). Within the UNFCCC climate negotiations, the projected inequality (Parikh, 1992) became a governing negotiation issue (Gupta and Hisschemöller, 1997; Okereke and Coventry, 2016) based on economic interests (Hecht and Tirpak, 1995; Oberthür and Ott, 1999) and injustice (Bos and Gupta, 2019). The global convergence assumptions became necessary because they represent drivers of emissions projections and explain the subsequent role in shaping UNFCCC policy negotiations, e.g., for the mitigation engagement of developing non-Annex-I countries.

A decade later, two letters to IPCC, published in a peer-reviewed journal, argued that the SRES used the wrong economic metrics (market-exchange rates (MER)). They argued that using MER disrupted the conditional convergence quantifications in the SRES-A1 and SRES-B1 scenarios (global convergence), leading to excessive economic growth assumptions in low-income regions, resulting in unrealistic high energy and emission levels (Castles and Henderson, 2003a, 2003b). IPCC authors accepted the suggested use of purchasing power parities (PPP) (Nakicenovic et al., 2003). Others stated that the non-peer-reviewed critique was misused to discredit climate change research (Van Vuuren and Alfsen, 2006) or a weak IPCC response (Tol, 2006). Because of limited PPP databases (starting from 1990 (WB, 2021)), historical PPP could not have been used in the SRES. Expert meetings and IPCC AR4 assessed PPP vs. MER-based scenarios (IPCC, 2007b, IPCC, 2005c). Successive research concluded that economic metrics had no significant influence on emissions ranges (Dixon and Rimmer, 2005; Holtsmark and Alfsen, 2005; IPCC, 2007b, 2005c; Manne et al., 2005; McKibbin et al., 2004; Pearce et al., 2004; Tol, 2006; Van Vuuren and Alfsen, 2006). In addition, the SRES assumptions of absolute emissions intensity convergence were questioned (Tol, 2006), showing weak evidence for *"absolute"* but strong evidence for energy per unit income "conditional" convergence (Miketa and Mulder, 2005).

Researchers assessed if the (historically limited) PPP-datasets could provide robust scenarios (Grübler et al., 2004; Nakicenovic et al., 2003; Nordhaus, 2005). The fourth scenario generation (SSP) included PPP metrics (Riahi et al., 2017) to compare the actual welfare levels across regions (Holtsmark and Alfsen, 2005; Van Vuuren and Alfsen, 2006).

During UK parliamentary hearings, an expert stated that IPCC was politicized, e.g., that the SRES regional GDP projections were adjusted upwards under pressure from African governments (House of Lords, 2005a).

5.1.2. Negative emissions technologies (NETs)

Because of continued policy delays, since the SA90 scenarios, it has become increasingly challenging to create low-emission scenarios aligned with the Paris Agreement. Thus, NETs gained a critical role in the modeling assumptions to achieve the Paris Agreement. NETs and assumptions on their costs became fundamental for the subsequent low emission pathway narratives (Gidden et al., 2019; IPCC, 2018a). The NETs ideas emerged in the late 1990s (Williams, 1998), describing that more CO_2 can be extracted from the atmosphere than released by humans. Throughout the 2000s, concepts like bioenergy with carbon capture and storage (BECCS) evolved further (Obersteiner, 2001), were picked up by models (Riahi et al., 2004, 2003; van Vuuren et al., 2007), and included in the Paris Agreement (UNFCCC, 2015). Modelers and other researchers explored deep mitigation scenarios (Mori, 2000; Roehrl and Riahi, 2000) with and without BECCS (Edmonds et al., 2013), arguing that it could lighten mitigation costs (Edmonds et al., 2013; Kriegler et al., 2013; van Vuuren et al., 2013). The low-emission stabilization scenarios presented in IPCC AR1-3 (based on SA90, IS92, and SRES) were different from the scenarios presented in AR4-5 (based on RCP/SSP-RCPs) (Matsuno et al., 2012). The latter included negative emissions (Vaughan and Gough, 2016) with a broader mitigation range than previous assessments (Smith and Porter, 2018). Allowing net negative emissions in the RCP2.6 scenario made it logical to overshoot and subsequently compensate with negative emissions. As a result, several 1.5 °C and 2 °C-pathways rely on 'net negative' global carbon from 2050 (Workman et al., 2020), withdrawing between 260 and 1080 Gt CO_2 between 2020 and 2100 (IPCC, 2018a).

Internally, RCP-developers debated the feasibility of RCP2.6 (IPCC, 2007a; Weyant et al., 2009). The IPCC AR5 assessment of RCP2.6 models (2 °C-pathways) led to a series of critiques. Researchers argued that modelers unintentionally hid the scale of NETs when reporting net carbon emissions (Anderson and Peters, 2016; Geden, 2016) in RCP2.6

Fig. 5. Distribution and development of critique topics. **a** The number of peer-reviewed scenario critiques by primary topic (intense colors) and secondary topics (light colors) analysis topics. Primary topics are given a score of 1. Secondary topics are given a score of 0.25, 0.5, or 0.75, equal to their weight and relevance in the paper. One primary topic was identified per paper, while it may address several secondary topics. **b** Primary topics & weighted secondary topics grouped by publication year. Based on 280 peer-reviewed articles published between 1990 and 2021 assessing SA90, IS92, SRES, SSP-RCPs, or SR1.5 emission scenario series (See SI excel, Sheet 1).

(Anderson, 2015; Fuss et al., 2014; Smith et al., 2016) and SP1.5 low-emission scenarios (Beck and Mahony, 2018a; Workman et al., 2020). Researchers addressed concerns related to technology developments merely being in a demonstration phase (Mander et al., 2018), the magnitude of NETs needed (Anderson, 2015; Fuss et al., 2014), and the required land-areas for biomass (Fuhrman et al., 2019) and power plants (Rayner, 2016). They found complications regarding competition for scarce resources, large-scale implementation (EASAC, 2018; Krause et al., 2018; Ricke et al., 2017), economic costs (Fuss et al., 2018; Moriarty and Honnery, 2018), biodiversity, food, and water scarcity concerns (Hejazi et al., 2014; Ohashi et al., 2019), and tradeoffs with achieving the other UN Sustainable Development Goals (SGDs; UNGA, 2015) more broadly in particular in the developing countries (Fuhrman et al., 2019). These were connected to a secondary critique of the policy implications (5.4.1). Modelers responded by addressing some potential issues regarding food security concerns (Fujimori et al., 2019, 2018; Hasegawa et al., 2018).

The public media saw NETs as dangerously optimistic (Carus, 2009) and overestimating technological advances (Edwards, 2020a; Kruger et al., 2016). As a response, SSP/RCP-developers provided more transparent IAM descriptions (Bauer et al., 2020), exploring alternative pathways (e.g., lifestyle, renewables) (van Vuuren et al., 2018). They also stated that, without current policy-action, NETs implementation beyond 2050 would be necessary to meet the Paris targets (Tanaka and O'Neill, 2018; Van Vuuren et al., 2017).

5.1.3. Energy system assumptions

Energy technologies and transitions are central mitigation drivers and inform policy responses. During RCP preparations (IPCC, 2007a), researchers debated SRES energy assumptions (Pielke et al., 2008; Richels et al., 2008; Smil, 2008) and technology transitions without policy intervention (Pielke et al., 2008; Smil, 2008). They argued that modelers underestimated the technological challenges of stabilizing GHG concentrations (Pielke et al., 2008). The recent high emissions growth generated questions on possible hidden (Field, 2008) and too optimistic technology assumptions (Richels et al., 2008; Smil, 2008) and energy transition costs (Richels et al., 2008). Others argued that the technologies for energy transition were (almost) available (Romm, 2008).

In 1997, scientists suggested that future CO_2 emissions ranges may be defined by geological limitations (Gregory and Rogner, 1998; Rogner, 1997). IPCC assessed the fossil resource availability (IPCC, 2001b), concluding that it would not limit carbon emissions by 2100 (IPCC, 2001a). Between 2008 and 2017, researchers assumed that fossil resources were infinite (Nel and Cooper, 2009). Researchers argued that supply-driven fossil energy assumptions (based on fossil reserves) would be more reliable than the demand-driven assumptions included in the SRES scenarios (Brecha, 2008; Höök and Tang, 2013; Wang et al., 2017. They questioned the plausibility of high-emission scenarios SRES-A1FI (Brecha, 2008; Höök, 2011) and RCP8.5 (Ritchie and Dowlatabadi, 2017; Wang et al., 2017). Scenario developers did not find these suggestions solid (O'Neill et al., 2019).[4]

5.2. Range of emission scenarios

5.2.1. Emission ranges: Too-high or too-low

Emissions ranges are essential for assessing needs for mitigation (low emission pathways) and adaptation (high emission (and impact) pathways). The scenario ranges have been questioned for being too low and too high throughout the past three decades, e.g., reassessing the low and high emission scenarios, respectively. During the 1990s, global emissions grew at a similar speed as projected in medium–low emissions pathways (Pedersen et al., 2021). During that period, researchers argued that the IS92 emissions range was too high (Gray, 1998). Between 1999 and 2012, the World experienced a high emissions growth period (Pedersen et al., 2021), making researchers argue the SRES and RCP scenario ranges as potentially too low (Le Quéré et al., 2009; Peters et al., 2013; Raupach et al., 2007; Sheehan, 2008). During the successive period of overall slower growth (2013–2019) (Pedersen et al., 2021), researchers suggested that the SSP-RCP range was potentially too high (Hausfather and Peters, 2020). Based on the assumptions underlying the scenarios, SRES and RCP emissions ranges were questioned as too low (Anderson, 2015; Castles and Henderson, 2003a; Fuss et al., 2014; Pielke et al., 2008) or too high (Burgess et al., 2021; Castles and Henderson, 2003a; Christensen et al., 2018; Sanderson et al., 2011). These critiques including climate analyses informed IPCC AR3 and AR4 (Anderson et al., 2008; Ganguly et al., 2009; Reichstein, 2010; Romm, 2008). Modelers and others pointed out that RCP8.5 tracks cumulative historical CO_2 emissions (Pedersen et al., 2020; Schwalm et al., 2020) and that historical emissions are within emissions ranges (van Vuuren and Riahi, 2008) and tracking medium–high pathways (Pedersen et al., 2020). Modelers emphasized the fundamental differences underlying short-term fluctuations versus significant long-term trend breaks (Manning et al., 2010; van Vuuren et al., 2010; van Vuuren and Riahi, 2008). The range critiques did not impact SSP-RCP emissions ranges (Riahi et al., 2017).

Public media followed the fluctuations of scientific critiques. They first hinted that IPCC exaggerated temperature projections (Corcoran, 2002; Economist, 2003a), potentially compromising IPCC reports' reliability and policy relevance (Economist, 2003b, Economist, 2003a). Later, they questioned if IPCC climate projections were too conservative (Keulemans, 2020; Scherer, 2012). Such appraisals were critical from a policy perspective since emissions, and climate projections, inform the climate negotiations and national policies (Garnaut et al., 2008).

5.2.2. Missing scenarios

Scenario series consist of a few selected scenarios out of an infinite number of possible futures. Therefore, some scenarios or key narratives may be overlooked. To complete the scenario framework, users have requested additional scenarios to be included. Examples are missing impact-conflict scenarios (Nordås and Gleditsch, 2007), intervention scenarios for mitigation and adaptation assessments (Schenk and Lensink, 2007), mitigation costs (Rogelj et al., 2013), more elaborated sustainability and vulnerability indicators like biodiversity (van Ruijven et al., 2013; Wilbanks and Ebi, 2014), food and water security (Fujimori et al., 2018; Hejazi et al., 2014), consumption (Girod et al., 2013), impacts on biodiversity (Otero et al., 2020; Raskin and Swart, 2020), and degrowth assumptions (Hickel et al., 2021; Otero et al., 2020). Several scenario assessments included climate impacts (Ansah et al., 2022; Hasegawa et al., 2018; Nordås and Gleditsch, 2007), not included in the SSPs. IPCC AR4, AR5, and SR1.5 elaborated on mitigation costs (Rogelj et al., 2013). However, these were not yet included in scenarios (IPCC, 2018a). SSP developers welcomed some missing scenario aspects to complete the SSPs (O'Neill et al., 2020).

Several researchers argued for additional research on local risks and drivers of change (Cradock-Henry et al., 2018), such as institutional capacities (van Ruijven et al., 2013; Wilbanks and Ebi, 2014). SRES and SSPs do not explore conflict and security pathways (Nordås and Gleditsch, 2007). Civil war may reduce regional economic growth (Devitt and Tol, 2012). Here variables like equality, governance, and literacy may induce pacifying effects that can be implemented in scenarios (Andrijevic et al., 2020; Hegre et al., 2016). IPCC AR5 found climate impacts to increase conflict risks (IPCC, 2014a). SSP modelers argue that global conflict and governance extensions will support the SSPs (O'Neill et al., 2020).

Some researchers and modelers argue that scenarios preferred by policymakers might constrain scientific imagination and downplay structural discontinuity (Raskin and Swart, 2020). They problematize that economic growth is built into models (and policies) (Krakauer, 2014), despite also driving climate and environmental problems (Otero et al., 2020). To project sustainable development scenarios need, assumptions on nature-people relationships (Otero et al., 2020; Rosa et al., 2020) and the UN Sustainable Development Goals (SDGs) (Kriegler et al., 2018). Researchers advocate an increased focus on fundamental global system transformations (David Tàbara et al., 2018), lifestyles, values, institutions (Raskin, 2005, 2000), and (weak) governance (Andrijevic et al., 2020). To guide policymakers, product developers, and consumers, modelers argued in favor of translating emission reductions into consumption levels (Girod et al., 2013). Additionally, international trade assumptions examining national emissions flows are less elaborated in the SSPs (Pedersen et al., 2021). SSP developers decided that narratives should inform analyses of global goals beyond those in the Paris Agreement (O'Neill et al., 2020).

Finally, researchers presented scenarios, including Solar Radiation

[4] At the Scenarios Forums 2019 (O'Neill et al., 2019), researchers addressed a plausible fossil fuel resource limit and its potential consequences for the upper limit of scenario emissions ranges (O'Neill et al., 2019), Here, one RCP/SSP author stated that they had already discussed this during the scenario's development process, without considering it plausible that fossil fuel limitations would affect the scenario ranges (Scenarios Forum 2019, University of Denver, March 12, Session 20).

Management (SRM) (Wigley, 2006), aiming to modify Earth's shortwave radiative budget (IPCC, 2018a). The SRES (Wigley, 2006), RCPs (Kravitz et al., 2011; Taylor et al., 2012), and SR1.5 were criticized for missing SRM scenarios (Reynolds, 2021). IPCC found SRM untested (IPCC, 2018a) with side effects and ethical implications (IPCC, 2014b).

5.3. Methodological issues

5.3.1. Development process

The author team, composition, and process may reflect the result of scenario assumptions. Before and during the IPCC period, researchers have challenged in-crowd-complications (Keepin and Wynne, 1984; Parikh, 1992) and stereotyped (western) discourses (Sardar, 1993; Thompson, 1984), limited insights (Castles and Henderson, 2003b), and self-fulfilling prophecies (Beck and Mahony, 2017) in modeling teams. This sometimes led to expanding the author team, e.g., range of researchers, scenario users, and stakeholder inclusions, to improve scenario relevance and credibility (O'Neill et al., 2020). Similar implications involved conflicting policy interests (Edenhofer and Kowarsch, 2015; Girod and Mieg, 2008), also reflected in climate negotiations within UNFCCC (Hecht and Tirpak, 1995; Oberthür and Ott, 1999). (O'Neill et al., 2020).

Others advocated stakeholder inclusion on multiple levels (Girod and Mieg, 2008; Kok et al., 2007; Schenk and Lensink, 2007), contributing to adding locally relevant details (Cradock-Henry et al., 2018). Intensified scenario critiques after AR3 put pressure on IPCC delegates (IPCC, 2003) who decided that IPCC should facilitate rather than develop new scenarios (IPCC, 2005a) following scenario expert meeting recommendations (IPCC, 2007c, 2007a, IPCC, 2005d, IPCC, 2005c). Simultaneously, researchers argued that low funding support in developing countries limited regional scenario specifications (Wilbanks and Ebi, 2014). Thus there is a need for increased local stakeholder inclusion (Cradock-Henry et al., 2018) to improve scenario developments (Kok et al., 2007), support local decisionmaking (Cradock-Henry et al., 2018; Workman et al., 2020), and assess the feasibility of mitigation pathway solutions (Anderson and Jewell, 2019; Weber et al., 2018). Others warned that including a broader diversity of government and non-state actor viewpoints might compromise scenario credibility (Beck and Mahony, 2017), recommending improved systematic processes and formalized methods for stakeholder engagement (Carlsen et al., 2017).

5.3.2. Methods applied

Since 2000, qualitative scenario aspects have been expressed in narrative form (IPCC, 2000a; Schweizer and Kriegler, 2012), aiming to ensure scenario logic and internal consistency (Nakicenovic and Swart, 2000). SRES authors criticized the initial SRES approach, "story and simulation" (SAS), as being limited (Alcamo, 2008). Coupling a storyline to a quantitative simulation (SAS method) does not sufficiently check for internal consistency (Kemp-Benedict, 2012; Schweizer and Kriegler, 2012). Furthermore, the contemporary current global pathway SRES-A1FI ('coal-powered growth') was argued to be under-represented. Instead, consistent and robust scenarios with this theme could be identified via the new CIB method (Cross-impact Balance) (Kemp-Benedict, 2012; Schweizer and Kriegler, 2012). The CIB was used for SSP developments. It identified internal inconsistency in SRES storylines (Schweizer and Kriegler, 2012) and found internally consistent combinations in all five SSP challenge space domains. However, 85% of combinations lay along the diagonal for Low, Medium, or High mitigation-adaptation-challenges (SSP5-SSP2-SSP1), with most of these in Medium and High domains (Schweizer and O'Neill, 2014). More recently, an advanced 'linked CIB' technique enables the analysis of large CIB matrices and ensures internally consistent linking of scenario elements across scales and matrices (Schweizer and Kurniawan, 2016).

In parallel, modelers proposed a backward approach to support SSP-storyline developments, focusing on the most relevant emission drivers to distinguish between, e.g., equity and convergence scenarios (Rozenberg et al., 2014) and systematically identify scenario groups with similar outcomes (Guivarch et al., 2016). Additionally, a method for transparent scenario selection, revealing vulnerabilities of proposed policies and considering scenario diversity, was introduced (Carlsen et al., 2016). A collection of papers proposed to derive policy-relevant insights from scenario developments. They aimed to identify novel research questions, examine how scenarios reflect equity (O'Neill and Nakicenovic, 2008), and how scenarios are used in scientific fields to provide a common framework for coordinating studies across research communities (O'Neill and Nakicenovic, 2008). It was further examined via the Scenarios Forum Conference (O'Neill et al., 2019) and elaborated by scenario developers (O'Neill et al., 2020).

5.3.3. Transparency

Users' understanding of scenarios, numbers, and narratives is essential for user trust and relevance (Pedersen et al., 2022), making transparency and scenario communication crucial. Since the 2000s, IAMs have been seen as complex (Ellenbeck and Lilliestam, 2019; Pindyck, 2017), unavoidably cloudy, containing implicit assumptions (Anderson and Bows, 2011), making scenarios challenging to interpret (Koomey et al., 2019). These target less explicit drivers (Girod et al., 2009; Koomey et al., 2019), (Field, 2008), hidden technology assumptions (Richels et al., 2008; Smil, 2008), unjustified decarbonization (Pielke et al., 2008), and re-carbonization (Ritchie and Dowlatabadi, 2018). Similarly, NETs critiques claim that modelers make culturally biased assumptions, use unrealistic input data, and subjectively decide the system's functions and the single parameters, which unintentionally risk masking model inconsistency (Ellenbeck and Lilliestam, 2019; Pindyck, 2017). Additionally, some of the changes in IS92 and SRES (Girod et al., 2009; IPCC, 2000b) were arguably political and less transparent (Girod et al., 2009). Researchers also questioned if RCP2.6 was a hidden co-production between RCP-modelers and EU policymakers (Beck and Mahony, 2017; Lövbrand, 2011), wondering how to organize this more inclusively (Beck and Mahony, 2017). New methods, comprising standardized scenario results, might support users to understand better the scenarios and their implications (Koomey et al., 2019). The SRES' open process was argued to increase transparency and legitimacy (Girod et al., 2009).

Lack of saliency across scenario series as regards the absence of intervention scenarios, storyline names, and labeling (Girod et al., 2009), was addressed by IPCC authors (van Vuuren et al., 2012) and more clearly labeled in the SSPs (Riahi et al., 2017). IPCC increased attention on assumptions and model approaches during the AR6 preparations (IPCC, 2017a). It published an SR1.5 database (IPCC, 2017b) without completely solving the IAM reproducibility and transparency challenges (Robertson, 2021). RCP/SSP authors provided more transparent descriptions of IAM assumptions on model structures, energy sectors, and bioenergy conversion chains (Bauer et al., 2020).

5.3.4. Higher resolution for impact assessments

National detail is essential for policymakers (Pedersen et al., 2022), mitigation, and adaptation assessments (Kok et al., 2007). In 2002, a small number of scenario assessments called for higher resolution, down-scaling scenarios for regional climate impact assessments (Arnell et al., 2004; Gaffin et al., 2004) associated with the objectives of WG2. The SRES team refrained from downscaling because meaningful top-down downscaling is very difficult, and higher precision levels would misrepresent associated uncertainties. Researchers later requested fine-grained climate data, incorporating geographic variation (Nordås and Gleditsch, 2007). The initial critiques led to a high-resolution database (i.e., population and GDP) developed by IPCC authors but independently of IPCC (CIESIN, 2002; Gaffin et al., 2004). National projections were prepared for the SSPs (Dellink et al., 2017; KC and Lutz, 2017).

Since scenarios mainly address the global scale (Zurek 2007), SSPs' ability to support national and local scale decisionmaking remains untested (Cradock-Henry et al., 2018). It is not always appropriate to tightly connect scenarios across scales (Biggs et al., 2007) since the global scale may alienate stakeholders at various administrative scales (Biggs et al., 2007; Kok et al., 2007). Also, the development of participatory scenarios at multiple scales (e.g., time scale, geographic scale) has a strong potential to contribute to decision making and coping with the existing tradeoff between maintaining relevance to stakeholders at different scales and maintaining consistency across scales (Kok et al., 2007). The global SSPs were prepared as a platform for developing extended SSPs substantive elaborations for specific sectors and regions, aiming to improve their usefulness for IAV studies (van Ruijven et al., 2013). Modelers encourage community consensus on methods for working with SSPs across scales (O'Neill et al., 2020). Furthermore, several IAMs are now open-source (e.g., MESSAGE, GCAM, and REMIND), and model description papers are available (Harmsen et al., 2021).

5.4. Policy relevance and implications

Policy relevance and implications represented crosscutting critique topics related to assessments of several assumptions, emission range, and process critiques.

5.4.1. Policy relevance

The earliest known scenario critique argued for extending emissions projections beyond 2100 to improve decisionmaking (Cline, 1991), which was included in the SSP-RCPs twenty-five years later (IPCC, 2007a). More recently, researchers argue that the translation of scenarios and scientific evidence into effective decisionmaking has been ineffective (Geden, 2016; Kok et al., 2007; Wilkinson and Eidinow, 2008). The model literature does not explain how researchers could more efficiently contribute to public discourses (Edenhofer and Kowarsch, 2015). On the one hand, scenarios need to be less complex and communicated in a simple manner (Pedersen et al., 2022; Schenk and Lensink, 2007). On the other hand, to ensure robust decisionmaking (Workman et al., 2020), they need regular updates (Garnaut et al., 2008; Peters et al., 2013), examining further the diverse regional emission growth (Anderson and Bows, 2011; Pedersen et al., 2020), including state and non-state viewpoints (Weber et al., 2018; Workman et al., 2020), identifying local policy interventions (David Tàbara et al., 2018; Pedersen et al., 2022), and including well-known mitigation benefits (not included in AR5) (Rosen and Guenther, 2016). According to SSP modelers, including the Paris goals and actual policies and their implications might improve low emission pathways (O'Neill et al., 2020).

5.4.2. Policy implications

Several previously elaborated critiques addressed the scenarios' potential policy implications, like energy assumptions (Nel and Cooper, 2009; Pielke et al., 2008), regional GDP (Castles and Henderson, 2003b; Parikh, 1992), NETs (Anderson, 2015), and missing scenario aspects (Schenk and Lensink, 2007) including paradigm changes (Raskin and Swart, 2020; Raskin, 2000). Models have been argued to reflect policymaker worldviews (Anderson, 2015; Geden, 2016; Haas, 2004), making them incomplete (Haas, 2004) and inappropriate policy tools (Pindyck, 2017). During 1998–2011 a group of papers opposed mitigation policy regulation as proposed via UNFCC. They presented this via scenario critiques and thus reached beyond the IAMs' roles, questioning anthropogenic climate change and the IPCC's knowledge monopoly, i.e., to inform policy options (Armstrong et al., 2011; Castles and Henderson, 2003b; Gray, 1998). This critique type ended with the RCPs but continued in the grey literature (Bezdek et al., 2019). They attracted the attention of political bodies (House of Lords, 2005b), the media (Economist, 2004, Economist, 2003b), and mitigation policy skeptics (Carter et al., 2006). IPCC modelers did not respond to the IPCC credibility critique. However, the IPCC addressed general IPCC criticism to improve IPCC communication (Lynn, 2016).

During the past decade, the fourth generation IAMs were argued to be black boxes, unfit for policymaking, culturally biased, and comprising unresolved uncertainties (Ellenbeck and Lilliestam, 2019; Low and Schäfer, 2020; Workman et al., 2020). The NETs (and SRM) critiques also stretch beyond the IAMs, questioning IPCC neutrality (Anderson and Peters, 2016; Geden, 2016; Hansson et al., 2021; Low and Schäfer, 2020) and a need to inform policymakers (Fuss et al., 2014). The high policymaker demand for mitigation scenarios implies risks that models end up saying what policymakers want to hear (Anderson, 2015; Geden, 2016), presenting assumptions (Anderson and Jewell, 2019; Anderson and Peters, 2016) that differ from the actual policy actions (Rayner, 2016). Therefore, policy-driven researchers and advisors, including scenario developments, should critically evaluate how their work is interpreted and used in policymaking processes (Geden, 2016) to adequately inform policy (Beck and Mahony, 2018a, 2018b). This also included implications regarding IAMs as boundary objects (Beck and Mahony, 2017; Hansson et al., 2021; Low and Schäfer, 2020). Public media replicated the critiques that IAMs contain unhealthy unproven doses of wishful thinking (Edwards, 2020b; Kruger et al., 2016). At the same time, the media also replicated scientific critiques of the scientific overuse of high-emissions pathways, which may mislead policy (Hausfather and Peters, 2020; Pielke and Ritchie, 2020). Additionally, that policymakers tend to focus on extreme scenarios (Höök, 2011). SSP developers announced a need for an increased focus on simplified communication (e.g., infographics and simpler IAMs) and better accessibility via developing an informative and user-friendly online database developed via stakeholder inclusion (O'Neill et al., 2020).

5.4.3. The role of scenarios

Since 2000, natural scientists have argued a need to include probability-based scenario designs (Allen et al., 2000; Schneider, 2001). Scenario developers defended using the explorative storyline approach (Grübler and Nakicenovic, 2001). The critics stated that the SRES does not sufficiently support decisionmaking, since policy analysts need probability estimates to assess the seriousness of the plausible climate impacts (Morgan and Keith, 2008; Schneider, 2001). Scholars argued that error bands and indications of likelihood might support decisionmaking (Schenk and Lensink, 2007; Schneider, 2001), simplify communication (Schenk and Lensink, 2007), and include an analyst's judgment about the probability of various futures (Morgan and Keith, 2008; Schneider, 2001).

SRES developers argued that natural scientific probability estimates might interfere with the scenario logic and the complex interconnection between emission drivers (Grübler and Nakicenovic, 2001). From a social science perspective, emission scenarios could not be represented by probabilities (Hulme 2004) because future emissions and aerosols fall into the category of "unknowable" knowledge, which depends on subjective judgments of unpredictable socioeconomic developments (Hulme 2000). To identify the most critical parameters (Webster et al., 2002), researchers explored probabilistic uncertainty in key drivers, such as population (Lutz et al., 2001) and technology (Gritsevskyi and Nakićenovi, 2000). Additionally, focusing on the output (radiative forcing) than on the input (emissions) may provide coverage of ranges and improve the probabilistic scenario design (IPCC, 2005c; Webster et al., 2002). At RCP/SSP expert meetings, developers discussed probability distributions and policymaker information. Probability was perceived as a subjective choice, potentially making policy choices expressed in probabilistic terms and probability assessment across storylines incorrect (IPCC, 2005b). AR4 compared what-if, probabilistic, and best-guess scenarios (IPCC, 2007b), while AR5 comprised results from 31 models and 1184 scenarios (IPCC, 2014c). Others, including SSP authors, found differences in long-term emission probabilities between expert estimates, which might result from factors like subjective assessments and model inability to foresee long-term disruptive changes (Ho et al., 2019). Researchers recently suggested qualitatively identifying the most likely (best-guess) scenarios based on current trends (Hausfather and Peters, 2020).

Besides a natural-social science opposition, the debate revealed disagreements between the climate and impact assessment communities. The first argued that probability analysis would support mitigation decisionmaking (Allen, 2003; Schneider, 2001; Webster et al., 2002) and more simple scenario communication (Hausfather and Peters, 2020; Pielke and Ritchie, 2020). On the contrary, the latter argued that robust adaptation policy solutions must be based on a wide range of plausible scenarios rather than best-guess (Lawrence et al., 2020; Lempert and Schlesinger, 2001).

6. Discussion

The review aimed to neutrally describe the criticism and how the scenario authors have addressed the criticism at the time. A neutral critique approach provides insights into the connection between critiques and responses and thus the scenarios' foundation and evolution.

6.1. Scenario changes

The review shows that scenario substance (assumptions and quantifications) and methodologies have changed over time. In the beginning, via intergovernmental arguments (IPCC, 1991). Later, changes occurred via scientific and IPCC evaluations (Alcamo et al., 1995; Parikh, 1992) guiding intergovernmental mandates (IPCC, 1996). Since 2000, the scenarios have evolved primarily via scientific critiques and assessments (IPCC, 2007a; O'Neill et al., 2020). Because of the nature of the IPCC, the IPCC panel agreed that experts should publish critique responses in peer-reviewed journals (IPCC, 2003). In addition, some key debates were addressed in IPCC sessions, expert meetings, and ARs, like economic metrics (IPCC, 2007b) and probability assessments (IPCC, 2014c). Seemingly the post-SRES scenarios were less visible as these SRES scenarios hardly attracted critique.

IPCC intergovernmental discussions affected scenario exercises at least three times and once raised the emission range's upper end (i.e., changing conditions for climate and response strategy assessments). We found no evidence that critiques significantly altered overall emissions ranges after 1992, although this is subject to a recurrent debate till today.

The critical letters sent to IPCC (Castles and Henderson, 2003a) addressed methodology and assumption critiques. It led to several scientific evaluations and changed the economic metric without significantly changing the non-OECD GDP range. Moreover, several missing scenario critiques were welcomed by SSP developers (O'Neill et al., 2020).

Methods have changed over time via assessments from SSP and other modelers. Also, the scenario development team has increased continuously. IPCC processes pushed the inclusion of economists in the second generation (IS92) (IPCC, 1991; Pepper et al., 1992), while critiques pushed the inclusion of non-OECD researchers and economic institutions in the third generation (SRES) (Castles and Henderson, 2003a; IPCC, 1996; Parikh, 1992). For the fourth generation (SSP-RCP), the IPCC panel recommended (IPCC, 2005a) including a wider variety and the number of non-governmental stakeholders, e.g., research communities, scenario user groups, and multilateral organizations (IPCC, 2007a).

The energy technology and fossil supply critiques drew low attention from modelers and did not affect assumptions nor ranges. The IPCC and developers have assessed critiques addressing policy issues, i.e., NETs, probability, and SRM. However, this did not lead to substantial scenario changes other than increasing transparency (e.g., improved databases). Only recently, user relevance and scenario communication have been explicitly expressed by modelers (O'Neill et al., 2020).

6.2. Imaginative capacity

The results demonstrate that substantial shortfalls in knowledge limit our understanding of the future. The future is explored partly on historical experiences, records, and trends and partly on our imaginative capacity. Several critiques advocate continuously exploring new possibilities within a series' chosen scenarios to remain science- and policy-relevant. Other critiques advocate being cautious and not too speculative. Some critiques implicitly targeted the (unrealistic) imaginative capacity of developers, like too optimistic regional GDP (Castles and Henderson, 2003a), global technology developments (Pielke et al., 2008), and some NETs critiques. However, historical non-OECD GDP and non-biomass renewable energy were within SRES ranges (Pedersen et al., 2021), and technology developments have been more rapid than expected (Creutzig et al., 2017). Despite this, such critiques play a role in 1) continuously challenging the modelers' perceptions, which shape assumptions, and 2) informing scenario users about plausible shortfalls. History will show how NETs will evolve, offering a plausible pathway toward reaching the Paris goals and informing about plausible mitigation tools. There are no indications that NETs assumptions will be excluded (Tanaka and O'Neill, 2018; Van Vuuren et al., 2017). Other critiques introduce alternative mitigation pathways and advocate increasing imaginative flexibility, e.g., degrowth and discontinuity scenarios (Otero et al., 2020; Raskin and Swart, 2020). The responses emphasize that not all scenarios in a series are realizable. Simultaneously, the critiques hint that scenario tools may inspire policy strategies via a wide band of plausible tools.

6.3. Transparency and communication

The critiques reveal a need to improve scenario communication and transparency to serve scenario uses in research and policymaking. Low transparency has led to critique. Already in 1984, energy models were accused of being hardwired, reaching specific outputs (Keepin and Wynne, 1984). Similarly, NETs critiques declared that models unintentionally risk masking model inconsistency (Anderson and Peters, 2016; Fuss et al., 2014) and that simpler tools may be more relevant for policymaking (Ellenbeck and Lilliestam, 2019; Pindyck, 2017). To facilitate a 'correct' use of scenarios, modelers propose improving scenario results via new approaches, like infographics, cartoons, and simplified illustrations of system dynamics and IAMs (O'Neill et al., 2020). Here the following could be emphasized:

More simple accessibility and overview of input and output data (transparency) and simple communication of the relationships between assumptions, drivers, and future developments (ensuring that users understand and use scenarios 'correctly'). Policy relevance and actionability may increase by highlighting policy tools and plausible implications. As an add-on, modelers could consider specific communication of assumed policy roadmaps with timetables of needed technology funding and implementation (to support monitoring policy actions and delays).

7. Conclusion

The review shows that scenario assumptions, quantifications, and methods have changed over time, inspired by political considerations and scientific critiques.

The subsequent scenario generations used in IPCC assessments have passed the test of criticism over time. Many critiques have scrutinized the scenarios, led to scenario improvements and enhanced their credibility. From a scientific perspective, the credibility may have been compromised because of excluding mitigation scenarios in IS92 and SRES. However, from a political perspective, this reduced scope was necessary to have the scenarios also accepted for consistent use in IPCC by countries that still questioned the need for mitigation. Later the mitigation need was globally accepted. As the RCP/SSP developments moved outside the IPCC, the scenarios' scope expanded to include mitigation as a component of sustainable futures.

Critiques can be grouped into various primary and secondary focus topics, revealing that half of the critiques addressed assumptions. In total, we identified 280 emission scenario critiques. They can be grouped into four main categories emerging from the literature: assumptions and scenario ranges (substance), and methodology and user relevance/policy issues (process).

Some of the critical themes in the critiques, MER-PPP (2003–2007) and the IPCC in-crowd (1998–2013), have been intense during specific periods but seem to have disappeared, while probability/best-guess have decreased in intensity. Scenario improvements took away some critique topics, like narratives including explicit income convergence and changed economic metrics. Improved development processes, such as increased author teams and stakeholder inclusion, took away several process critiques (while the IPCC critical literature continued in the grey literature). The probability critiques evolved during the transition period between the second and third generations (IS92 and SRES) and faded after 2013. However, critiques recently advocated adding qualitative likelihoods or best guesses to the SSP-RCP framework.

Some themes have continued to be relevant. The most prominent examples are assumptions, emission ranges (since IS92), resolution, and applied methods (since SRES). Although experts and stakeholders have increasingly been included in scenario developments, stakeholder inclusion in scenario preparations and local extensions continues to be addressed in the literature addressing resolution/local extensions and non-government mitigation actions.

Policy implications and transparency critiques have emerged more recently. These critiques were also addressed as secondary topics in NETs critiques. Furthermore, has missing scenario critiques (adding new aspects to the narratives) become more frequent. These critique topics might continue to be relevant in the future.

The scenario critiques do emphasize the importance of communication and transparency. Although probability critiques did not significantly change the scenarios, they advocated for more uncomplicated scenario communication, which developers recently considered. Scenarios have grown more complex over time; thus, it may be valuable to include user perspectives (e.g., policymakers, sectorial stakeholders) to develop effective scenario communication in the future.

Not only scenarios include subjective choices. Also, the assessed critiques have (implicit and explicit) politically motivated aims, such as convergence assessments, critiques questioning the IPCC status, if policy regulation is needed, and missing Solar Radiation Management. Others were more neutral, contributing to later scenario developments, e.g., probability critiques focusing on outputs (radiative forcing) or effective communicating scenarios. To further improve the knowledge of IPCC assessments' effectiveness and the role of emissions scenarios, more research would be required into the sources of sponsorship of critiques and the grey literature.

CRediT authorship contribution statement

Jiesper Tristan Strandsbjerg Pedersen: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft. **Detlef van Vuuren:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **Joyeeta Gupta:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – review & editing. **Filipe Duarte Santos:** Formal analysis, Investigation, Resources, Supervision, Validation, Writing – review & editing. **Jae Edmonds:** Supervision, Validation, Writing – review & editing. **Rob Swart:** Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to acknowledge the graphical support from Kaj-Ivar van der Wijst for visualizing the excellent overview illustration in Fig. 5b and SI Fig. 1 (PBL Netherlands Environmental Assessment Agency and Copernicus Institute of Sustainable Development, Utrecht University). Additionally, the authors would like to acknowledge the financial support from EEA-Financial Mechanism 2014-2021 and the Portuguese Environment Agency through the Pre-defined Project-2 National Roadmap for Adaptation XXI (PDP-2).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2022.102538.

References

Alcamo, J., 2008. Chapter six the SAS approach: combining qualitative and quantitative knowledge in environmental scenarios. Develop. Integrated Environ. Assessm. https://doi.org/10.1016/S1574-101X(08)00406-7.

Alcamo, J., Bouwman, A., Edmonds, J., Grubler, A., Morita, T., Sugandhy, A., 1995. An Evaluation of the IPCC IS92 Emission Scenarios, in: Climate Change 1994. Radiative Forcing of Climate Change and an Evaluation of the IPCC 1992 IS92 Emission Scenarios. Intergovernmental Panel on Climate Change. IIASA Research Report (Reprint), IIASA, Laxenburg, Austria: RR-95-010, pp. 247–304.

Allen, M.R., 2003. Climate forecasting: possible or probable? Nature 425, 242–242. 10.1038/425242a.

Allen, M.R., Stott, P.A., Mitchell, J.F.B., Schnur, R., Delworth, T.L., 2000. Quantifying the uncertainty in forecasts of anthropogenic climate change. Nature 407 (6804), 617–620.

Anderson, K., 2015. Duality in climate science. Nat. Geosci. 8, 898–900. https://doi.org/10.1038/ngeo2559.

Anderson, K., Bows, A., 2011. Beyond 'dangerous' climate change: emission scenarios for a new world. Philos. Trans. R. Soc. A: Mathem., Phys. Eng. Sci. 369, 20–44. https://doi.org/10.1098/rsta.2010.0290.

Anderson, K., Bows, A., Mander, S., 2008. From long-term targets to cumulative emission pathways: reframing UK climate policy. Energy Policy 36, 3714–3722. https://doi.org/10.1016/J.ENPOL.2008.07.003.

Anderson, K., Jewell, J., 2019. Debating the bedrock of climate-change mitigation scenarios. Nature 573, 348–349. https://doi.org/10.1038/d41586-019-02744-9.

Anderson, K., Peters, G., 2016. The trouble with negative emissions. Science (1979) 354, 182–183. 10.1126/science.aah4567.

Andrijevic, M., Crespo Cuaresma, J., Muttarak, R., Schleussner, C.F., 2020. Governance in socioeconomic pathways and its role for future adaptive capacity. Nat. Sustainability 3, 35–41. https://doi.org/10.1038/s41893-019-0405-0.

Ansah, M.K., Chen, X.i., Yang, H., 2022. A holistic environmental and economic design optimization of low carbon buildings considering climate change and confounding factors. Sci. Total Environ. 821, 153442.

Armstrong, J.S., Green, K.C., Soon, W., 2011. Research on forecasting for the manmade global warming alarm. Energy Environ. 22 (8), 1091–1104.

Arnell, N.W., Livermore, M.J.L., Kovats, S., Levy, P.E., Nicholls, R., Parry, M.L., Gaffin, S. R., 2004. Climate and socio-economic scenarios for global-scale climate change impacts assessments: characterising the SRES storylines. Global Environ. Change 14, 3–20. https://doi.org/10.1016/j.gloenvcha.2003.10.004.

Baranzelli, C., Vandecasteele, I., Batista E Silva, F., Rojas Mujica, R., Lavalle, C., 2013. Implementation of the IPCC SRES Scenario A1B with the Land Use Modelling Platform. Luxembourg (Luxembourg). 10.2788/62013.

Bauer, N., Rose, S.K., Fujimori, S., van Vuuren, D.P., Weyant, J., Wise, M., Cui, Y., Daioglou, V., Gidden, M.J., Kato, E., Kitous, A., Leblanc, F., Sands, R., Sano, F., Strefler, J., Tsutsui, J., Bibas, R., Fricko, O., Hasegawa, T., Klein, D., Kurosawa, A., Mima, S., Muratori, M., 2020. Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. Clim. Change 163, 1553–1568. https://doi.org/10.1007/s10584-018-2226-y.

Beck, S., Mahony, M., 2018a. The politics of anticipation: the IPCC and the negative emissions technologies experience. Global Sustainability 1, 1–8. https://doi.org/10.1017/sus.2018.7.

Beck, S., Mahony, M., 2018b. The IPCC and the new map of science and politics. WIREs Clim. Change 9. https://doi.org/10.1002/wcc.547.

Beck, S., Mahony, M., 2017. The IPCC and the politics of anticipation. Nat. Clim. Change 7, 311–313. https://doi.org/10.1038/nclimate3264.

Bellamy, R., Healey, P., 2018. 'Slippery slope' or 'uphill struggle'? Broadening out expert scenarios of climate engineering research and development. Environ. Sci. Policy 83, 1–10. https://doi.org/10.1016/j.envsci.2018.01.021.

Bezdek, R., Idso, C.D., Legates, D., Singer, S.F., Avery, D., Dunn, J.D., Monckton, C., Moore, P., Steele, C.N., Stover, A., Stroup, R.L., Arnett, J., Baden, J., Ball, T., Bast, J.

L., Battig, C., Briggs, E., Brill, B., Dayaratna, K., Enstrom, J.E., Forbes, D.K., Frank, P., Haapala, K., Hayden, H., Hayward, T.B., Lehr, J., Leyland, B., Milloy, S., Soon, W., Trzupek, R., Welcenbach, S., Young, S.S., Allen, D.W., Alliegro, M., Anderson, C., Archibald, D., Avery, D.T., Bowen, D., Burnett, H.S., Burton, D., Butos, W.N., Campbell, M., Chapas, J.D., Clark, I.D., Crowe, D.R., Cui, W., Dears, D., Deming, D., Donze, T.W., Driessen, P., Droz, J., Fleming, R.J., Forbes, V.R., Gerhard, L.C., Gervais, F., Glatzle, A., Goreham, S., Gosselin, P., Gould, L., Green, K., Harde, H., Harris, T., Hennigan, T., Hertzmark, D., Humlum, O., Hutzler, M., Johnsen, H.K., Joondeph, B., Keen, R.A., Kininmonth, W., Leimkuhler, J., Lewis, M., Lupo, A.R., Mcfadyen, P., Merrifield, J., Moran, A., Murphy, R., Nebert, D.W., Page, N.J., Palmer, F., Paltridge, G., Petch, J., Rombough, C.T., Rychlak, R., Segalstad, T. V, Sharp, G.D., Solheim, J.-E., Stevenson, D., Stilbs, P., Sutter, D., Tattersol, R., Tipler, F., Vahrenholt, F., Viterito, A., Walin, G., Wallace, L., Walton, T.F., Wanliss, J., Weinstein, B.L., Bast, D.C., 2019. Climate Change Reconsidered II: Fossil Fuels (NIPCC).

Biggs, R., Raudsepp-Hearne, C., Atkinson-Palombo, C., Bohensky, E., Boyd, E., Cundill, G., Fox, H., Ingram, S., Kok, K., Spehar, S., Tengö, M., Timmer, D., Zurek, M., 2007. Linking futures across scales: a dialog on multiscale scenarios. Ecol. Soc. 12 https://doi.org/10.5751/ES-02051-120117.

Bolin, B., 2007. A History of the Science and Politics of Climate Change: The Role of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York.

Bos, K., Gupta, J., 2019. Stranded assets and stranded resources: Implications for climate change mitigation and global sustainable development. Energy Res. Social Sci. 56, 101215 https://doi.org/10.1016/J.ERSS.2019.05.025.

Brecha, R.J., 2008. Emission scenarios in the face of fossil-fuel peaking. Energy Policy 36, 3492–3504. https://doi.org/10.1016/j.enpol.2008.05.023.

Burgess, M.G., Ritchie, J., Shapland, J., Pielke, R., 2020. IPCC baseline scenarios have over-projected CO2 emissions and economic growth. Environ. Res. Lett. 16, 014016. 10.1088/1748-9326/abcdd2.

Carlsen, H., Klein, R.J.T., Wikman-Svahn, P., 2017. Transparent scenario development. Nat. Climate Change 7, 613. 10.1038/nclimate3379.

Carlsen, H., Lempert, R., Wikman-Svahn, P., Schweizer, V., 2016. Choosing small sets of policy-relevant scenarios by combining vulnerability and diversity approaches. Environ. Modell. Software 84, 155–164. https://doi.org/10.1016/j.envsoft.2016.06.011.

Carter, R.M., de Freitas, C.R., Goklany, I.M., Holland, D., Lindzen, R.S., Byatt, I., Castles, I., Goklany, I.M., Henderson, D., Lawson, N., McKitrick, R., Morris, J., Peacock, A., Robinson, C., Skidelsky, R., 2006. The stern review: a dual critique. World Econ. 7, 68.

Carus, F., 2009. UK climate change policies "dangerously optimistic", MPs warned. The Guardian.

Castles, I., Henderson, D., 2003a. The IPCC emission scenarios: an economic-statistical critique. Energy Environ. 14, 159–185. https://doi.org/10.1260/095830503765184583.

Castles, I., Henderson, D., 2003b. Economics, emissions scenarios and the work of the IPCC. Energy Environ. 14, 415–435. https://doi.org/10.1260/095830503322364430.

Christensen, P., Gillingham, K., Nordhaus, W., 2018. Uncertainty in forecasts of long-run economic growth. Proc. Natl. Acad. Sci. 115, 5409–5414. https://doi.org/10.1073/pnas.1713628115.

Ciesin, 2002. Country-Level Population and Downscaled Projections based on the B2 Scenario, 1990–2100 [digital version]. Center for International Earth Science Information Network (CIESIN), CIESIN, Columbia University, Palisades, NY.

Cline, W.R., 1991. Scientific basis for the greenhouse effect. Econ. J. 101, 904–919.

Corcoran, T., 2002. An "insult to science". National Post 4.

Cradock-Henry, N.A., Frame, B., Preston, B.L., Reisinger, A., Rothman, D.S., 2018. Dynamic adaptive pathways in downscaled climate change scenarios. Clim. Change 150, 333–341. https://doi.org/10.1007/s10584-018-2270-7.

Creutzig, F., Agoston, P., Goldschmidt, J.C., Luderer, GunnarCreutzig, F., Nemet, G., Pietzcker, R.C., 2017. The underestimated potential of solar energy to mitigate climate change. Nat. Energy. 10.1038/nenergy.2017.140.

David Tàbara, J., Frantzeskaki, N., Hölscher, K., Pedde, S., Kok, K., Lamperti, F., Christensen, J.H., Jäger, J., Berry, P., 2018. Positive tipping points in a rapidly warming world. Curr. Opin. Environ. Sustainability. https://doi.org/10.1016/j.cosust.2018.01.012.

Dellink, R., Chateau, J., Lanzi, E., Magné, B., 2017. Long-term economic growth projections in the shared socioeconomic pathways. Global Environ. Change 42, 200–214. https://doi.org/10.1016/j.gloenvcha.2015.06.004.

Dessai, S., Hulme, M., 2004. Does climate adaptation policy need probabilities? Climate Policy. https://doi.org/10.1080/14693062.2004.9685515.

Devitt, C., Tol, R.S., 2012. Civil war, climate change, and development: a scenario study for sub-Saharan Africa. J. Peace Res. 49, 129–145. https://doi.org/10.1177/0022343311427417.

Dixon, P.B., Rimmer, M.T., 2005. Analysing convergence with a multi-country computable general equilibrium model: PPP versus Mer. Energy Environ. 16, 901–921. https://doi.org/10.1260/095830505775221524.

EASAC, 2018. Science Advice for the Benefit of Europe Negative emission technologies: What role in meeting Paris Agreement targets?

Economist, 2004. Measuring economies – Garbage in, garbage out [WWW Document]. The Economist. URL https://www.economist.com/leaders/2004/05/27/garbage-in-garbage-out (accessed 3.4.21).

Economist, 2003a. Hot potato revisited.

Economist, 2003b. Hot potato. The Economist.

Edenhofer, O., Kowarsch, M., 2015. Cartography of pathways: A new model for environmental policy assessments. Environ. Sci. Policy 51, 56–64. 10.1016/J.ENVSCI.2015.03.017.

Edmonds, J., Luckow, P., Calvin, K., Wise, M., Dooley, J., Kyle, P., Kim, S.H., Patel, P., Clarke, L., 2013. Can radiative forcing be limited to 2.6 Wm−2 without negative emissions from bioenergy AND CO2 capture and storage? Clim. Change 118, 29–43. https://doi.org/10.1007/s10584-012-0678-z.

Edmonds, J.A., Mintzer, I., Pepper, W., Major, K., Schater, V., Wise, M., Baron, R., 1992. Comparison of Reference Case Global Fossil Carbon Emissions. Washington D.C.

Edwards, T., 2020a. Negative-emissions tech helps, but it's no magic bullet for the climate crisis. The Guardian.

Edwards, T., 2020b. Negative emissions tech helps, but it's no magic bullet for the climate crisis [WWW Document]. accessed 10.21.20 The Guardian. https://www.theguardian.com/commentisfree/2020/jul/20/negative-emissions-tech-climate-crisis-carbon.

Ellenbeck, S., Lilliestam, J., 2019. How modelers construct energy costs: Discursive elements in Energy System and Integrated Assessment Models. Energy Res. Social Sci. 47, 69–77. https://doi.org/10.1016/J.ERSS.2018.08.021.

EMF, 2020. Energy Modeling Forum [WWW Document]. Energy Modeling Forum. URL https://emf.stanford.edu/.

Fawcett, A.A., Iyer, G.C., Clarke, L.E., Edmonds, J.A., Hultman, N.E., McJeon, H.C., Rogelj, J., Schuler, R., Alsalam, J., Asrar, G.R., Creason, J., Jeong, M., McFarland, J., Mundra, A., Shi, W., 2015. Can Paris pledges avert severe climate change? Science 1979 (350), 1168–1169. https://doi.org/10.1126/science.aad5761.

Field, C.B., 2008. Energy assumptions were reasonable at the time, but not now. Nature 453, 154–155. https://doi.org/10.1038/453154b.

Fuhrman, J., McJeon, H., Doney, S.C., Shobe, W., Clarens, A.F., 2019. From zero to hero?: why integrated assessment modeling of negative emissions technologies is hard and how we can do better. Front. Climate 11. https://doi.org/10.3389/FCLIM.2019.00011.

Fujimori, S., Hasegawa, T., Krey, V., Riahi, K., Bertram, C., Bodirsky, B.L., Bosetti, V., Callen, J., Després, J., Doelman, J., Drouet, L., Emmerling, J., Frank, S., Fricko, O., Havlik, P., Humpenöder, F., Koopman, J.F.L., van Meijl, H., Ochi, Y., Popp, A., Schmitz, A., Takahashi, K., van Vuuren, D., 2019. A multi-model assessment of food security implications of climate change mitigation. Nat. Sustainability 2019 2:5 2, 386–396. 10.1038/s41893-019-0286-2.

Fujimori, S., Hasegawa, T., Rogelj, J., Su, X., Havlik, P., Krey, V., Takahashi, K., Riahi, K., 2018. Inclusive climate change mitigation and food security policy under 1.5 °C climate goal. Environ. Res. Lett. 13, 074033 https://doi.org/10.1088/1748-9326/AAD0F7.

Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P., Jackson, R.B., Jones, C.D., Kraxner, F., Nakicenovic, N., le Quéré, C., Raupach, M.R., Sharifi, A., Smith, P., Yamagata, Y., 2014. Betting on negative emissions. Nat. Clim. Change 4, 850–853. https://doi.org/10.1038/nclimate2392.

Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente, J.L.V., Wilcox, J., del Mar Zamora Dominguez, M., Minx, J.C., 2018. Negative emissions—Part 2: Costs, potentials and side effects. Environ. Res. Lett. 13, 063002. 10.1088/1748-9326/aabf9f.

Gaffin, S.R., Rosenzweig, C., Xing, X., Yetman, G., 2004. Downscaling and geo-spatial gridding of socio-economic projections from the IPCC Special Report on Emissions Scenarios (SRES). Global Environ. Change 14, 105–123. https://doi.org/10.1016/j.gloenvcha.2004.02.004.

Ganguly, A.R., Steinhaeuser, K., Erickson, D.J., Branstetter, M., Parish, E.S., Singh, N., Drake, J.B., Buja, L., 2009. Higher trends but larger uncertainty and geographic variability in 21st century temperature and heat waves. Proc. Natl. Acad. Sci. U.S.A. 106, 15555–15559. https://doi.org/10.1073/pnas.0904495106.

Garnaut, R., Howes, S., Jotzo, F., Sheehan, P., 2008. Emissions in the Platinum Age: the implications of rapid development for climate-change mitigation. Oxford Rev. Econ. Policy 24, 377–401. https://doi.org/10.1093/oxrep/grn021.

Geden, O., 2016. The Paris Agreement and the inherent inconsistency of climate policymaking. Wiley Interdiscip. Rev. Clim. Change 7, 790–797. https://doi.org/10.1002/wcc.427.

Gidden, M.J., Riahi, K., Smith, S.J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren, D. P., van den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J.C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R., Horing, J., Popp, A., Stehfest, E., Takahashi, K., 2019. Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. Geosci. Model Dev. 12, 1443–1475. https://doi.org/10.5194/gmd-12-1443-2019.

Gidden, M.J., Riahi, K., Smith, S.J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren, D. P., van den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J.C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R., Horing, J., Popp, A., Stehfest, E., Takahashi, K., 2018. Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. Geosci. Model Dev. Discuss. 1–42 https://doi.org/10.5194/gmd-2018-266.

Girod, B., Mieg, H., 2008. Scientific and Political Reasons for Changes in the IPCC Scenarios Series. Gaia-Ecological Perspectives for Science and Society.

Girod, B., van Vuuren, D.P., Hertwich, E.G., 2013. Global climate targets and future consumption level: an evaluation of the required GHG intensity. Environ. Res. Lett. 8.

Girod, B., Wiek, A., Mieg, H., Hulme, M., 2009. The evolution of the IPCC's emissions scenarios. Environ. Sci. Policy 12, 103–118. https://doi.org/10.1016/j.envsci.2008.12.006.

Gray, V., 1998. The IPCC future projections: are they plausible? Climate Res.

Gregory, K., Rogner, H.H., 1998. Energy resources and conversion technologies for the 21(st) century. Mitig. Adapt. Strat. Glob. Change 3, 171–230. https://doi.org/10.1023/a:1009674820623.

Gritsevskyi, A., Nakićenovi, N., 2000. Modeling uncertainty of induced technological change. Energy Policy 28, 907–921. https://doi.org/10.1016/S0301-4215(00)00082-3.
Grübler, A., Nakicenovic, N., 2001. Identifying dangers in an uncertain climate. Nature 412, 15. https://doi.org/10.1038/35083752.
Grübler, A., Nakicenovic, N., Alcamo, J., Davis, G., Fenhann, J., Hare, B., Mori, S., Pepper, B., Pitcher, H., Riahi, K., Rogner, H.-H., La Rovere, E.L., Sankovski, A., Schlesinger, M., Shukla, R.P., Swart, R., Victor, N., Jung, T.Y., 2004. Emissions scenarios: a final response. Energy Environ. 15, 11–24. https://doi.org/10.1260/095830504322986466.
Guivarch, C., Rozenberg, J., Schweizer, V., 2016. The diversity of socio-economic pathways and CO2 emissions scenarios: insights from the investigation of a scenarios database. Environ. Modell. Software 80, 336–353. https://doi.org/10.1016/j.envsoft.2016.03.006.
Gupta, J., Hisschemöller, M., 1997. Issue-linkages: a global strategy towards sustainable development. Int. Environ. Affairs 9, 289–308.
Haas, P.M., 2004. When does power listen to truth? a constructivist approach to the policy process. J. Eur. Public Policy. https://doi.org/10.1080/1350176042000248034.
Hansson, A., Anshelm, J., Fridahl, M., Haikola, S., 2021. Boundary Work and Interpretations in the IPCC Review Process of the Role of Bioenergy With Carbon Capture and Storage (BECCS) in Limiting Global Warming to 1.5°C. Front. Climate 3. 10.3389/FCLIM.2021.643224.
Harmsen, M., Kriegler, E., van Vuuren, D.P., van der Wijst, K.I., Luderer, G., Cui, R., Dessens, O., Drouet, L., Emmerling, J., Morris, J.F., Fosse, F., Fragkiadakis, D., Fragkiadakis, K., Fragkos, P., Fricko, O., Fujimori, S., Gernaat, D., Guivarch, C., Iyer, G., Karkatsoulis, P., Keppo, I., Keramidas, K., Köberle, A., Kolp, P., Krey, V., Krüger, C., Leblanc, F., Mittal, S., Paltsev, S., Rochedo, P., van Ruijven, B.J., Sands, R.D., Sano, F., Strefler, J., Arroyo, E.V., Wada, K., Zakeri, B., 2021. Integrated assessment model diagnostics: key indicators and model evolution. Environ. Res. Lett. 16, 054046 https://doi.org/10.1088/1748-9326/ABF964.
Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B.L., Doelman, J.C., Fellmann, T., Kyle, P., Koopman, J.F.L., Lotze-Campen, H., Mason-D'Croz, D., Ochi, Y., Pérez Domínguez, I., Stehfest, E., Sulser, T.B., Tabeau, A., Takahashi, K., Takakura, J., van Meijl, H., van Zeist, W.J., Wiebe, K., Witzke, P., 2018. Risk of increased food insecurity under stringent global climate change mitigation policy. Nat. Clim. Change 2018 8:8 8, 699–703. 10.1038/s41558-018-0230-x.
Hausfather, Z., Peters, G.P., 2020. Emissions – the 'business as usual' story is misleading. Nature 577, 618–620. https://doi.org/10.1038/d41586-020-00177-3.
Hecht, A.D., Tirpak, D., 1995. Framework agreement on climate change: a scientific and policy history. Clim. Change 29, 371–402. https://doi.org/10.1007/BF01092424.
Hegre, H., Buhaug, H., Calvin, K.V., Nordkvelle, J., Waldhoff, S.T., Gilmore, E., 2016. Forecasting civil conflict along the shared socioeconomic pathways. Environ. Res. Lett. 11, 054002 https://doi.org/10.1088/1748-9326/11/5/054002.
Hejazi, M.I., Edmonds, J., Clarke, L., Kyle, P., Davies, E., Chaturvedi, V., Wise, M., Patel, P., Eom, J., Calvin, K., 2014. Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies. Hydrol. Earth Syst. Sci. 18, 2859–2883. https://doi.org/10.5194/HESS-18-2859-2014.
Hickel, J., Brockway, P., Kallis, G., Keyßer, L., Lenzen, M., Slameršak, A., Steinberger, J., Ürge-Vorsatz, D., 2021. Urgent need for post-growth climate mitigation scenarios. Nat. Energy 2021 6:8 6, 766–768. 10.1038/s41560-021-00884-9.
Ho, E., Budescu, D.V., Bosetti, V., van Vuuren, D.P., Keller, K., 2019. Not all carbon dioxide emission scenarios are equally likely: a subjective expert assessment. Clim. Change 155, 545–561. https://doi.org/10.1007/s10584-019-02500-y.
Holtsmark, B.J., Alfsen, K.H., 2005. PPP correction of the IPCC emission scenarios? does it matter? Clim. Change 68, 11–19. https://doi.org/10.1007/s10584-005-1310-2.
Höök, M., 2011. Future coal production outlooks in the IPCC emission scenarios: are they plausible? Energy Environ. 22, 837–858. https://doi.org/10.1260/0958-305X.22.7.837.
Höök, M., Tang, X., 2013. Depletion of fossil fuels and anthropogenic climate change—a review. Energy Policy 52, 797–809. https://doi.org/10.1016/J.ENPOL.2012.10.046.
House of Lords, 2005a. Forecasting greenhouse gas emissions and Temperature Change, in: Economic Affairs Committee, Economic Affairs: 2nd Report of Session 2005-06. Voloume 2: Evidence. UK Parliament.
House of Lords, 2005b. The Economics of Climate Change. 2nd Report of Session 2005-06. Voloume 2: Evidence. London, UK.
IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Cambridge University Press.
IPCC, 2018a. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. Geneva, Switzerland.
IPCC, 2018b. Summary for Policymakers of IPCC Special Report on Global Warming of 1.5°C approved by governments. IPCC Press release 4.
IPCC, 2017a. Report of the forty-fifth session of the IPCC. Guadalajara, Mexico, 28-31 March 2017.
IPCC, 2017b. IPCCSR15 Scenario Database, 2017 [WWW Document]. URL https://db1.ene.iiasa.ac.at/IPCCSR15DB/.
IPCC, 2014a. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
IPCC, 2014b. 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. Geneva, Switzerland.
IPCC, 2014c. Climate Change 2014 Mitigation of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
IPCC, 2007a. Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies: Technical Summary. Noordwijkerhout, The Netherlands, 19–21 September, 2007.
IPCC, 2007b. AR4 Climate Change 2007: Mitigation of Climate Change.
IPCC, 2007c. Report of the 26th session of the IPCC. Bangkok, April 30-May 4, 2007.
IPCC, 2006. Report of the 25th session of the IPCC (Port Louis, Mauritius, 26-28 April 2006). Port Louis, Mauritius.
IPCC, 2005a. Report of the 24th Session of the IPCC (Montreal, 26-28 September 2005). Montreal, 22-28 September 2005.
IPCC, 2005b. IPCC Expert meeting on emission scenarios: meeting report. 12-14 January, Washingto DC. 10.1007/BF02986817.
IPCC, 2005c. IPCC Expert meeting on emission scenarios, 12-14 January 2005, Washington. Washington DC.
IPCC, 2005d. Workshop on New Emission Scenarios 29 June – 1 July 2005 (Meeting report). Laxenburg, Austria.
IPCC, 2003. Report of the 21st Session of the IPCC (Vienna, Austria, 3 and 6-7 November 2003). Wienna. 10.4324/9781315270326-109.
IPCC, 2001a. Climate Change 2001: Mitigation.
IPCC, 2001b. Climate Change 2001. Working Group I: The Scientific Basis.
IPCC, 2000a. IPCC Special Report: Emission Scenarios. Summary for Policymakers. A Special Report of IPCC Working Group III.
IPCC, 2000b. Comments on the SRES second order draft (open archive). Bilthoven.
IPCC, 1996. Report of the Twelfth Session of the IPCC. Mexico City, 11-13 September, 1996.
IPCC, 1995. Climate Change 1995: Economic and Social Dimensions of Climate Change. Contribution of Working Group III. Cambridge, England & Melbourne, Australia.
IPCC, 1991. Report of the 6th Session of the IPCC [WWW Document]. URL https://www.ipcc.ch/meetings/session06/sixth-session-report.pdf.
IPCC, 1990a. Climate Change: The IPCC Response Strategies, Working Group III.
IPCC, 1990b. Climate Change: The IPCC Scientific Assessment (1990). Cambridge, New York, Port Chester, Melbourne, Sydney.
IPCC, 1990c. Emissions scenarios: Appendix report of the Expert Group on Emission Scenarios, in: Tirpak, D., Velinga, P., Swart, R., Elzen, M. den, Rotmans, J. (Eds.), Climate Change: The IPCC Response Strategies. The Response Strategies Working Group (RSWG) of the Intergovernmental Panel on Climate Change (IPCC), p. 231.
IPCC, 1990d. Report of 3rd Session of the IPCC, Washington D.C., 5 - 7 February 1990. Washington D.C.
IPCC, 1989a. Report of the First Session of the IPCC Bureau. Geneva, 6-7 February, 1989.
IPCC, 1989b. Report of the Second Session of the WMO/UNEP Intergovernmental Panel on Climate Change (IPCC). World Meteorological Organization (WMO) & United Nations Environment Programme (UNEP).
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. Global Environ. Change 42, 181–192. 10.1016/j.gloenvcha.2014.06.004.
Keepin, B., Wynne, B., 1984. Technical analysis of IIASA energy scenarios. Nature 312, 691–695. https://doi.org/10.1038/312691a0.
Kemp-Benedict, E., 2012. Telling better stories: Strengthening the story in story and simulation. Environ. Res. Lett. 10.1088/1748-9326/7/4/041004.
Keulemans, M., 2020. Zó erg wordt het ook weer niet met het klimaat: hoe het rampscenario de bovenhand krijgt. de Volkskrant.
Kok, K., Biggs, R. (Oonsie), Zurek, M., 2007. Methods for Developing multiscale participatory scenarios: insights from Southern Africa and Europe. Ecol. Soc. 12.
Koomey, J., Schmidt, Z., Hummel, H., Weyant, J., 2019. Inside the Black Box: Understanding key drivers of global emission scenarios. Environ. Modell. Software 111, 268–281. https://doi.org/10.1016/J.ENVSOFT.2018.08.019.
Krakauer, N.Y., 2014. Economic growth assumptions in climate and energy policy. Sustainability (Switzerland) 6, 1448–1461. https://doi.org/10.3390/su6031448.
Krause, A., Pugh, T.A.M., Bayer, A.D., Li, W., Leung, F., Bondeau, A., Doelman, J.C., Humpenöder, F., Anthoni, P., Bodirsky, B.L., Ciais, P., Müller, C., Murray-Tortarolo, G., Olin, S., Popp, A., Sitch, S., Stehfest, E., Arneth, A., 2018. Large uncertainty in carbon uptake potential of land-based climate-change mitigation efforts. Glob. Change Biol. 24, 3025–3038. https://doi.org/10.1111/gcb.14144.
Kravitz, B., Robock, A., Boucher, O., Schmidt, H., Taylor, K.E., Stenchikov, G., Schulz, M., 2011. The geoengineering model intercomparison project (GeoMIP). Atmospheric Sci. Lett. Atmos. Sci. Let. 10.1002/asl.316.
Kriegler, E., Edenhofer, O., Reuster, L., Luderer, G., Klein, D., 2013. Is atmospheric carbon dioxide removal a game changer for climate change mitigation? Clim. Change 118, 45–57. https://doi.org/10.1007/s10584-012-0681-4.
Kriegler, E., Edmonds, J., Hallegatte, S., Ebi, K.L., Kram, T., Riahi, K., Winkler, H., van Vuuren, D.P., 2014. A new scenario framework for climate change research: the concept of shared climate policy assumptions. Clim. Change 122, 401–414. https://doi.org/10.1007/s10584-013-0971-5.
Kriegler, E., Huppman, D., Riahi, K., Rogelj, J., 2017. Request for 1.5C Emissions Scenario Data in support of the IPCC's Special Report on Global Warming of 1.5C.
Kriegler, E., Messner, D., Nakicenovic, N., Riahi, K., Rockström, J., Sachs, J., van der Leeuw, S., van Vuuren, D., 2018. Transformations to Achieve the Sustainable Development Goals Report prepared by The World in 2050 initiative. International Institute for Applied Systems Analysis (IIASA).
Kruger, T., Geden, O., Rayner, S., 2016. Abandon hype in climate models [WWW Document]. accessed 10.21.20 The Guardian. https://www.theguardian.com/science/political-science/2016/apr/26/abandon-hype-in-climate-models.

Lawrence, J., Haasnoot, M., Lempert, R., 2020. Climate change: making decisions in the face of deep uncertainty. Nature 580, 456–456. 10.1038/d41586-020-01147-5.

Le Quéré, C., Raupach, M.R., Canadell, J.G., Marland, G., Bopp, L., Ciais, P., Conway, T. J., Doney, S.C., Feely, R.A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R.A., House, J.I., Huntingford, C., Levy, P.E., Lomas, M.R., Majkut, J., Metzl, N., Ometto, J.P., Peters, G.P., Prentice, I.C., Randerson, J.T., Running, S.W., Sarmiento, J.L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G.R., Woodward, F.I., 2009. Trends in the sources and sinks of carbon dioxide. Nat. Geosci. 2, 831–836. https://doi.org/10.1038/ngeo689.

Leggett, J., Pepper, W.J., Swart, R.J., Edmonds, J., Meira Filho, L.G., Mintzer, I., Wang, M.X., Wasson, J., 1992. Emissions scenarios for the IPCC: an update, in: Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment. pp. 69–95.

Lempert, R., Schlesinger, M.E., 2001. Climate-change strategy needs to be robust. Nature. https://doi.org/10.1038/35086617.

Lövbrand, E., 2011. Co-producing European climate science and policy: a cautionary note on the making of useful knowledge. Sci. Public Policy 38, 225–236. https://doi.org/10.3152/030234211X12924093660516.

Low, S., Schäfer, S., 2020. Is bio-energy carbon capture and storage (BECCS) feasible? The contested authority of integrated assessment modeling. Energy Res. Social Sci. 60, 101326 https://doi.org/10.1016/j.erss.2019.101326.

Lutz, W., Sanderson, W., Scherbov, S., 2001. The end of world population growth. Nature 412, 543–545. https://doi.org/10.1038/35087589.

Lynn, J., 2016. IPCC communications issues – constraints and opportunities. Oslo.

Mander, S., Anderson, K., Larkin, A., Gough, C., Vaughan, N., 2018. The Climate-Change Mitigation Challenge, in: Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions. John Wiley & Sons, Ltd, pp. 187–203. 10.1002/9781119237716.CH9.

Manne, A.S., Richels, R.G., Edmonds, J.A., 2005. Market exchange rates or purchasing power parity: does the choice make a difference to the climate debate? Clim. Change 71, 1–8. https://doi.org/10.1007/s10584-005-0470-4.

Manning, M.R., Edmonds, J., Emori, S., Grubler, A., Hibbard, K., Joos, F., Kainuma, M., Keeling, R.F., Kram, T., Manning, A.C., Meinshausen, M., Moss, R., Nakicenovic, N., Riahi, K., Rose, S.K., Smith, S., Swart, R., van Vuuren, D.P., 2010. Misrepresentation of the IPCC CO2 emission scenarios. Nat. Geosci. 3, 376–377. https://doi.org/10.1038/ngeo880.

Matsuno, T., Maruyama, K., Tsutsui, J., 2012. Stabilization of atmospheric carbon dioxide via zero emissions-an alternative way to a stable global environment. Part 2: A practical zero-emissions scenario. Proc. Japan Acad., Series B 88, 385–395. https://doi.org/10.2183/pjab.88.385.

McKibbin, W.J., Pearce, D., Stegman, A., 2004. Can the IPCC SRES Be improved? Energy Environ. 15, 351–362. https://doi.org/10.1260/0958305041494611.

Miketa, A., Mulder, P., 2005. Energy productivity across developed and developing countries in 10 manufacturing sectors: patterns of growth and convergence. Energy Econ. 27, 429–453. https://doi.org/10.1016/j.eneco.2005.01.004.

Morgan, M.G., Keith, D.W., 2008. Improving the way we think about projecting future energy use and emissions of carbon dioxide. Clim. Change 90, 189–215. https://doi.org/10.1007/s10584-008-9458-1.

Mori, S., 2000. The development of greenhouse gas emissions scenarios using an extension of the MARIA model for the assessment of resource and energy technologies. Technol. Forecast. Soc. Chang. 63, 289–311. https://doi.org/10.1016/S0040-1625(99)00102-X.

Moriarty, P., Honnery, D., 2018. Energy policy and economics under climate change. AIMS Energy 6, 272–290. https://doi.org/10.3934/energy.2018.2.272.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756. https://doi.org/10.1038/nature08823.

Nakicenovic, N., Grübler, A., Gaffin, S., Jung, T.T., Kram, T., Morita, T., Pitcher, H., Riahi, K., Schlesinger, M., Shukla, P.R., van Vuuren, D., Davis, G., Michaelis, L., Swart, R., Victor, N., 2003. IPCC SRES revisited: a response. Energy Environ. 14, 187–214. https://doi.org/10.1260/095830503765184592.

Nakicenovic, N., Swart, R., 2000. Special Report on Emissions Scenarios. Cambridge University Press, Cambridge, UK.

Nel, W.P., Cooper, C.J., 2009. Implications of fossil fuel constraints on economic growth and global warming. Energy Policy 37, 166–180. https://doi.org/10.1016/J.ENPOL.2008.08.013.

Nordås, R., Gleditsch, N.P., 2007. Climate change and conflict. Political Geography 26, 627–638. https://doi.org/10.1016/j.polgeo.2007.06.003.

Nordhaus, W.D., 2005. Should modelers use purchasing power parity or market exchange rates in global modelling systems, in: Seminar on Emission Scenarios, Intergovernmental Panel on Climate Change (IPCC), 12-14th January. pp. 4–5, 30–31.

Obersteiner, M., 2001. Managing Climate Risk. Science (1979) 294, 786b–7787. 10.1126/science.294.5543.786b.

Oberthür, S., Ott, H.E., 1999. The Kyoto Protocol. Springer, Berlin Heidelberg, Berlin, Heidelberg, 10.1007/978-3-662-03925-0.

Ohashi, H., Hasegawa, T., Hirata, A., Fujimori, S., Takahashi, K., Tsuyama, I., Nakao, K., Kominami, Y., Tanaka, N., Hijioka, Y., Matsui, T., 2019. Biodiversity can benefit from climate stabilization despite adverse side effects of land-based mitigation. Nature Communications 2019 10:1 10, 1–11. 10.1038/s41467-019-13241-y.

Okereke, C., Coventry, P., 2016. Climate justice and the international regime: before, during, and after Paris. Wiley Interdiscip. Rev. Clim. Change 7, 834–851. https://doi.org/10.1002/wcc.419.

O'Neill, B.C., Carter, T.R., Ebi, K., Harrison, P.A., Kemp-Benedict, E., Kok, K., Kriegler, E., Preston, B.L., Riahi, K., Sillmann, J., van Ruijven, B.J., van Vuuren, D., Carlisle, D., Conde, C., Fuglestvedt, J., Green, C., Hasegawa, T., Leininger, J., Monteith, S., Pichs-Madruga, R., 2020. Achievements and needs for the climate change scenario framework. Nat. Clim. Change. https://doi.org/10.1038/s41558-020-00952-0.

O'Neill, B.C., Conde, C., Ebi, K., Friedlingstein, P., Fuglestvedt, J., Hasegawa, T., Kok, K., Kriegler, E., Monteith, S., Pichs-Madruga, R., Preston, B., Sillman, J., van Ruijven, B., van Vuuren, D., 2019. Forum on Scenarios of Climate and Societal Futures: Meeting Report. Pardee Center Working Paper 2019.10.04. Denver, Colorado, United States.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environ. Change 42, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004.

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Change 122, 387–400. https://doi.org/10.1007/s10584-013-0905-2.

O'Neill, B.C., Nakicenovic, N., 2008. Learning from global emissions scenarios. Environ. Res. Lett. 3, 45014–45023. https://doi.org/10.1088/1748-9326/3/4/045014.

O'Neill, B.C., Tebaldi, C., van Vuuren, D.P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G.A., Moss, R., Riahi, K., Sanderson, B.M., 2016. The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geosci. Model Dev. 9, 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016.

Oreskes, N., Shrader-Frechette, K., Belitz, K., 1994. Verification, validation, and confirmation o f numerical models i n the earth sciences verification. Problem "Truth" 263, 641.

Otero, I., Farrell, K.N., Pueyo, S., Kallis, G., Kehoe, L., Haberl, H., Plutzar, C., Hobson, P., García-Márquez, J., Rodríguez-Labajos, B., Martin, J., Erb, K., Schindler, S., Nielsen, J., Skorin, T., Settele, J., Essl, F., Gómez-Baggethun, E., Brotons, L., Rabitsch, W., Schneider, F., Pe'er, G., 2020. Biodiversity policy beyond economic growth. Conservation Letters 13. 10.1111/conl.12713.

Parikh, J.K., 1992. IPCC strategies unfair to the South. Nature. https://doi.org/10.1038/360507a0.

Pearce, D., Stegman, A., McKibbin, W., 2004. Long run projections for climate change scenarios.

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

Pedersen, J.S.T., Gomes, C.M., Gupta, J., van Vuuren, D., Santos, F.D., Swart, R., 2022. The policy-relevance of emission scenarios: policymakers require simpler, relevant, and more communicative scenarios. SSRN Electronic J. https://doi.org/10.2139/SSRN.4073175.

Pedersen, J.S.T., van Vuuren, D.P., Aparício, B.A., Swart, R., Gupta, J., Santos, F.D., 2020. Variability in historical emissions trends suggests a need for a wide range of global scenarios and regional analyses. Commun. Earth Environ. 1–7 https://doi.org/10.1038/s43247-020-00045-y.

Pepper, W.J., Leggett, R.J., Swart, R.J., Wasson, J., Edmonds, J., Mintzer, I., 1992. Emission Scenarios for the IPCC. An Update. Assumptions, Methodology, and Results. Washington, D.C.

Peters, G.P., Andrew, R.M., Boden, T., Canadell, J.G., Ciais, P., Le Quéré, C., Marland, G., Raupach, M.R., Wilson, C., 2013. The challenge to keep global warming below 2 °C. Nat. Clim. Change 3, 4–6. https://doi.org/10.1038/nclimate1783.

Pielke, R., Ritchie, J., 2020. Systemic misuse of scenarios in climate research and assessment. SSRN Electr. J. https://doi.org/10.2139/ssrn.3581777.

Pielke, R., Wigley, T., Green, C., 2008. Dangerous assumptions. Nature 452, 531–532. https://doi.org/10.1038/452531a.

Pindyck, R.S., 2017. The use and misuse of models for climate policy. Rev. Environ. Econ. Policy 11, 100–114. https://doi.org/10.1093/reep/rew012.

Raskin, P., Monks, F., Ribeiro, T., van Vuuren, D., Zurek, M., 2005. Global Scenarios in Historical Perspective [WWW Document]. Ecosystems and Human Well-Being: Scenarios: Findings of the Scenarios Working Group. URL https://pdfs.semanticscholar.org/780d/43ae4d93304b3d4d31f229656fd1d2aa02d5.pdf.

Raskin, P., Swart, R., 2020. Excluded futures: the continuity bias in scenario assessments. Sustainable Earth 3, 1–5. https://doi.org/10.1186/s42055-020-00030-5.

Raskin, P.D., 2005. Global scenarios: background review for the millennium ecosystem assessment. Ecosystems. https://doi.org/10.1007/s10021-004-0074-2.

Raskin, P.D., 2000. Bending the curve: toward global sustainability. Development (Basingstoke) 43, 67–74. https://doi.org/10.1057/palgrave.development.1110199.

Raupach, M.R., Marland, G., Ciais, P., Le Quéré, C., Canadell, J.G., Klepper, G., Field, C. B., 2007. Global and regional drivers of accelerating CO2 emissions. Proc Natl Acad Sci U S A 104, 10288–10293. https://doi.org/10.1073/pnas.0700609104.

Rayner, S., 2016. What might Evans-Pritchard have made of two degrees? Anthropology Today 32, 1–2. https://doi.org/10.1111/1467-8322.12263.

Reichstein, M., 2010. Journal club. Nature 2010 (464), 7286.

Reynolds, J.L., 2021. Is solar geoengineering ungovernable? a critical assessment of governance challenges identified by the Intergovernmental Panel on Climate Change. WIREs Clim. Change 12, e690.

Riahi, K., Rubin, E.S., Schrattenholzer, L., 2004. Prospects for carbon capture and sequestration technologies assuming their technological learning. Energy 29, 1309–1318. https://doi.org/10.1016/J.ENERGY.2004.03.089.

Riahi, K., Rubin, E.S., Schrattenholzer, L., 2003. Prospects for Carbon Capture and Sequestration Technologies Assuming Their Technological Learning. Greenhouse

Gas Control Technologies - 6th International Conference 1095–1100. 10.1016/B978-008044276-1/50173-2.
Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environ. Change 42, 153–168. 10.1016/j.gloenvcha.2016.05.009.
Richels, R.G., Tol, R.S.J., Yohe, G.W., 2008. Future scenarios for emissions need continual adjustment. Nature 453, 155–155. 10.1038/453155a.
Ricke, K.L., Millar, R.J., MacMartin, D.G., 2017. Constraints on global temperature target overshoot. Sci. Rep. 7, 14743. https://doi.org/10.1038/s41598-017-14503-9.
Ritchie, J., Dowlatabadi, H., 2018. Defining climate change scenario characteristics with a phase space of cumulative primary energy and carbon intensity. Environ. Res. Lett. 13 https://doi.org/10.1088/1748-9326/aaa494.
Ritchie, J., Dowlatabadi, H., 2017. Why do climate change scenarios return to coal? Energy 140, 1276–1291. https://doi.org/10.1016/J.ENERGY.2017.08.083.
Robertson, S., 2021. Transparency, trust, and integrated assessment models: An ethical consideration for the Intergovernmental Panel on Climate Change. WIREs Clim. Change 12. https://doi.org/10.1002/wcc.679.
Roehrl, R.A., Riahi, K., 2000. Technology dynamics and greenhouse gas emissions mitigation: a cost assessment. Technol. Forecast. Soc. Chang. 63, 231–261. https://doi.org/10.1016/S0040-1625(99)00112-2.
Rogelj, J., Mccollum, D.L., Reisinger, A., Meinshausen, M., Riahi, K., 2013. Probabilistic cost estimates for climate change mitigation. 10.1038/nature11787.
Rogner, H.-H., 1997. An assessment of world hydrocarbon resources. Annu. Rev. Energy Env. 22, 217–262. https://doi.org/10.1146/annurev.energy.22.1.217.
Romm, J., 2008. IPCC's climate-policy assumptions were justified. Nature 453, 155–155. 10.1038/453155c.
Rosa, I.M.D., Purvis, A., Alkemade, R., Chaplin-Kramer, R., Ferrier, S., Guerra, C.A., Hurtt, G., Kim, H., Leadley, P., Martins, I.S., Popp, A., Schipper, A.M., van Vuuren, D., Pereira, H.M., 2020. Challenges in producing policy-relevant global scenarios of biodiversity and ecosystem services. Global Ecol. Conserv. 22, e00886.
Rosen, R.A., Guenther, E., 2016. The energy policy relevance of the 2014 IPCC Working Group III report on the macro-economics of mitigating climate change. Energy Policy 93, 330–334. https://doi.org/10.1016/j.enpol.2016.03.025.
Rozenberg, J., Guivarch, C., Lempert, R., Hallegatte, S., 2014. Building SSPs for climate policy analysis: A scenario elicitation methodology to map the space of possible future challenges to mitigation and adaptation. Clim. Change 122, 509–522. https://doi.org/10.1007/s10584-013-0904-3.
Sanderson, B.M., O'Neill, B.C., Kiehl, J.T., Meehl, G.A., Knutti, R., Washington, W.M., 2011. The response of the climate system to very high greenhouse gas emission scenarios. Environ. Res. Lett. 6 https://doi.org/10.1088/1748-9326/6/3/034005.
Sardar, Z., 1993. Colonizing the future: the 'other' dimension of futures studies. Futures 25, 179–187. https://doi.org/10.1016/0016-3287(93)90163-N.
Schenk, N.J., Lensink, S.M., 2007. Communicating uncertainty in the IPCC's greenhouse gas emissions scenarios. Clim. Change 82, 293–308. https://doi.org/10.1007/s10584-006-9194-3.
Scherer, G., 2012. How the IPCC underestimated climate change. Sci. Am.
Schneider, S.H., 2001. What is "dangerous" climate change? Nature 411, 17–19. https://doi.org/10.1038/35075167.
Schwalm, C.R., Glendon, S., Duffy, P.B., 2020. RCP8.5 tracks cumulative CO2 emissions. Proceedings of the National Academy of Sciences 117, 202007117. 10.1073/pnas.2007117117.
Schweizer, V.J., Kriegler, E., 2012. Improving environmental change research with systematic techniques for qualitative scenarios. Environ. Res. Lett. 7, 44011–44025. https://doi.org/10.1088/1748-9326/7/4/044011.
Schweizer, V.J., Kurniawan, J.H., 2016. Systematically linking qualitative elements of scenarios across levels, scales, and sectors. Environ. Modell. Software 79, 322–333. https://doi.org/10.1016/j.envsoft.2015.12.014.
Schweizer, V.J., O'Neill, B.C., 2014. Systematic construction of global socioeconomic pathways using internally consistent element combinations. Clim. Change 122, 431–445. https://doi.org/10.1007/s10584-013-0908-z.
Sheehan, P., 2008. The new global growth path: implications for climate change analysis and policy. Clim. Change 91, 211–231. https://doi.org/10.1007/s10584-008-9415-z.
Smil, V., 2008. Long-range energy forecasts are no more than fairy tales. Nature 453, 154–154. 10.1038/453154a.
Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2016. Biophysical and economic limits to negative CO2 emissions. Nat. Clim. Change 6, 42–50. https://doi.org/10.1038/nclimate2870.
Smith, P., Porter, J.R., 2018. Bioenergy in the IPCC Assessments. GCB Bioenergy 10, 428–431. https://doi.org/10.1111/gcbb.12514.
Tanaka, K., O'Neill, B.C., 2018. The Paris Agreement zero-emissions goal is not always consistent with the 1.5 °C and 2 °C temperature targets. Nat. Clim. Change 8, 319–324. https://doi.org/10.1038/s41558-018-0097-x.
Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. Bull. Am. Meteorol. Soc. https://doi.org/10.1175/BAMS-D-11-00094.1.
Thompson, M., 1984. Among the Energy Tribes: A cultural framework for the analysis and design of energy policy. Policy Sci. 17, 321–339. https://doi.org/10.1007/BF00138710.
Tol, R.S.J., 2006. Exchange rates and climate change: an application of FUND. Clim. Change 75, 59–80. https://doi.org/10.1007/s10584-005-9003-4.
UNEP, 2020. Emissions Gap Emissions Gap Report 2020.
UNFCCC, 2021. Nationally determined contributions under the Paris Agreement Synthesis report by the secretariat, Conference of the Parties serving as the meeting of the Parties to the Paris Agreement Third session Glasgow, 1–12 November 2021. Glasgow, Ireland.
UNFCCC, 2015. Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015 (29 January 2016). Paris.
UNFCCC, 1992. United Nations Framework Convention on Climate Change. Parties of the Convention, New York.
UNFCCC/COP, 2015. Paris Agreement, United Nations Framework Convention on Climate Change. Paris, France.
Unga, 2015. Transforming our world: the 2030 Agenda for Sustainable Development Transforming our world: the 2030 Agenda for Sustainable Development Preamble. United Nations General Assembly.
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 Environ. Change 65, 102191. https://doi.org/10.1016/j.gloenvcha.2020.102191.
van Ruijven, B.J., Levy, M.A., Agrawal, A., Biermann, F., Birkmann, J., Carter, T.R., Ebi, K.L., Garschagen, M., Jones, B., Jones, R., Kemp-Benedict, E., Kok, M., Kok, K., Lemos, M.C., Lucas, P.L., Orlove, B., Pachauri, S., Parris, T.M., Patwardhan, A., Petersen, A., Preston, B.L., Ribot, J., Rothman, D.S., Schweizer, V.J., 2013. Enhancing the relevance of Shared Socioeconomic Pathways for climate change impacts, adaptation and vulnerability research. Clim. Change 122, 481–494. https://doi.org/10.1007/s10584-013-0931-0.
Van Vuuren, D.P., Alfsen, K.H., 2006. PPP versus mer: searching for answers in a multi-dimensional debate. Clim. Change 75, 47–57. https://doi.org/10.1007/s10584-005-9045-7.
van Vuuren, D.P., Deetman, S., van Vliet, J., van den Berg, M., van Ruijven, B.J., Koelbl, B., 2013. The role of negative CO2 emissions for reaching 2 °C—insights from integrated assessment modelling. Clim. Change 118, 15–27. https://doi.org/10.1007/s10584-012-0680-5.
van Vuuren, D.P., den Elzen, M.G.J., Lucas, P.L., Eickhout, B., Strengers, B.J., van Ruijven, B., Wonink, S., van Houdt, R., 2007. Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Clim. Change 81, 119–159. https://doi.org/10.1007/s10584-006-9172-9.
van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. Clim. Change 109, 5–31. https://doi.org/10.1007/s10584-011-0148-z.
van Vuuren, D.P., Edmonds, J., Smith, S.J., Calvin, K. v., Karas, J., Kainuma, M., Nakicenovic, N., Riahi, K., van Ruijven, B.J., Swart, R., Thomson, A., 2010. What do near-term observations tell us about long-term developments in greenhouse gas emissions? Climatic Change 103, 635–642. 10.1007/s10584-010-9940-4.
Van Vuuren, D.P., Hof, A.F., Van Sluisveld, M.A.E., Riahi, K., 2017. Open discussion of negative emissions is urgently needed. Nat. Energy 2, 902–904. https://doi.org/10.1038/s41560-017-0055-2.
van Vuuren, D.P., Kok, M.T.J., Girod, B., Lucas, P.L., de Vries, B., 2012. Scenarios in global environmental assessments: key characteristics and lessons for future use. Global Environ. Change 22, 884–895. https://doi.org/10.1016/J.GLOENVCHA.2012.06.001.
van Vuuren, D.P., O'Neill, B.C., 2006. The consistency of IPCC's SRES scenarios to 1990–2000 trends and recent projections. Clim. Change 75, 9–46. https://doi.org/10.1007/s10584-005-9031-0.
van Vuuren, D.P., Riahi, K., 2008. Do recent emission trends imply higher emissions forever? Clim. Change 91, 237–248. https://doi.org/10.1007/s10584-008-9485-y.
van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., van den Berg, M., Bijl, D.L., de Boer, H. S., Daioglou, V., Doelman, J.C., Edelenbosch, O.Y., Harmsen, M., Hof, A.F., van Sluisveld, M.A.E., 2018. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. Nat. Clim. Change 2018 8:5 8, 391–397. 10.1038/s41558-018-0119-8.
Vaughan, N.E., Gough, C., 2016. Expert assessment concludes negative emissions scenarios may not deliver. Environ. Res. Lett. 11, 095003 https://doi.org/10.1088/1748-9326/11/9/095003.
Wang, J., Feng, L., Tang, X., Bentley, Y., Höök, M., 2017. The implications of fossil fuel supply constraints on climate change projections: a supply-side analysis. Futures 86, 58–72. https://doi.org/10.1016/J.FUTURES.2016.04.007.
WB, 2021. GDP, PPP (constant 2017 international $) [WWW Document]. The World Bank. URL https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD?locations=IN (accessed 6.30.21).
Weber, C., McCollum, D.L., Edmonds, J., Faria, P., Pyanet, A., Rogelj, J., Tavoni, M., Thoma, J., Kriegler, E., 2018. Mitigation scenarios must cater to new users. Nat. Clim. Change. https://doi.org/10.1038/s41558-018-0293-8.
Webster, M.D., Babiker, M., Mayer, M., Reilly, J.M., Harnisch, J., Hyman, R., Sarofim, M. C., Wang, C., 2002. Uncertainty in emissions projections for climate models. Atmos. Environ. 36, 3659–3670. https://doi.org/10.1016/S1352-2310(02)00245-5.
Weyant, J., Azar, C., Kainuma, M., Kejun, J., Nakicenovic, N., Shukla, P.R., Rovere, E. La, Yohe, G., 2009. Report of 2.6 Versus 2.9 Watts/m2 RCPP Evaluation Panel.

Wigley, T.M.L., 2006. A combined mitigation/geoengineering approach to climate stabilization. Science 1979 (314), 452–454. https://doi.org/10.1126/science.1131728.

Wilbanks, T.J., Ebi, K.L., 2014. SSPs from an impact and adaptation perspective. Clim. Change 122, 473–479. https://doi.org/10.1007/s10584-013-0903-4.

Wilkinson, A., Eidinow, E., 2008. Evolving practices in environmental scenarios: a new scenario typology. Environ. Res. Lett. 3 https://doi.org/10.1088/1748-9326/3/4/045017.

Williams, R.H., 1998. Fuel decarbonization for fuel cell applications and sequestration of the separated CO2, in: Ayres, R.U., Weaver, P.M. (Paul M. (Eds.), Eco-Restructuring : Implications for Sustainable Development. United Nations University Press.

Workman, M., Dooley, K., Lomax, G., Maltby, J., Darch, G., 2020. Decision making in contexts of deep uncertainty – an alternative approach for long-term climate policy. Environ. Sci. Policy 103, 77–84. https://doi.org/10.1016/J.ENVSCI.2019.10.002.